ECONOMIC IMPORTANCE OF PEGMATITES

BY PAUL M. TYLER

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by

Paul M. Tyler[1/]

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INTRODUCTION

According to Lindgren[2/], the economic importance of pegmatites stems from the fact that they represent the principal natural storehouse of two classes of mineral products: (1) common minerals in exceptional size and purity and (2) several of the rarest minerals, which are not commercially available from other types of deposits.

Most pegmatites can be described simply as coarse- to very coarse-grained granites. Pegmatite includes coarse-textured igneous rocks of any composition, such as syenitic, alkali syenitic, dioritic, or gabbroitic; but basic pegmatites are far less common than those that are associated with acid rocks and correspond approximately to the mineral composition of ordinary granite. Moreover, only a very few basic pegmatites can be considered as economic sources of useful minerals.

Whereas, in ordinary granitic rocks the individual minerals usually measure 1/8 to 1/4 inch across, in pegmatites they are characteristically over 1 inch and often more than 12 inches in diameter. Although some of the constituents of the pegmatite may be only a fraction of an inch in length, single crystals more than 10 feet long are by no means unusual, and some crystals are enormous. A whole quarry was operated in the Urals within a single crystal of feldspar. Huge quartz crystals are quite common although usually imperfect. Muscovite plates 10 feet in diameter have been mined in India, and the Purdy mica mine in Canada contained a mica crystal measuring 6.5 by 9.5 feet and weighing nearly 7 tons, which supplied more than $20,000 worth of trimmed mica sheet. A loglike crystal of spodumene in the Etta mine in the Black Hills of South Dakota was 42 feet long. Giant crystals of beryl weighing several tons apiece have been mined from several properties.

Because so many rare minerals are found in substantial concentration only in pegmatites, it is a common fallacy to suppose that pegmatites are always enriched in rare elements. Traces of most of these elements, of course, are found in almost all igneous rocks, and they reappear in the sediments derived from igneous rocks. It does not follow, however, that all or even most pegmatites contain higher percentages of rare elements than other granitic rocks. Geological evidence points to the probability that notable concentrations of rarer minerals or elements in pegmatites are more or less fortuituous, such additions often being ascribed to events subsequent to the original emplacement of the main body of the pegmatite. Most pegmatites consist principally of potash, feldspar, and quartz. Even mica, although commonly present, is not an essential constituent. Probably only 1 or 2 in 100 pegmatites are of even potential economic importance

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2/ See alphabetical list of geologic references at end of paper.

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under present conditions, and most of those that are minable can yield only one or two economic minerals.

From the economic standpoint, perhaps the most striking feature of pegmatites is their apparent irregularity and variableness. No two are quite alike. Not only does each pegmatite body seem to be a law unto itself, but different parts of a single deposit may exhibit marked differences in texture, mineral composition, width, and attitude. Progress is being made, however, toward a better understanding of the nature of these deposits. Generalizations, as they are based on the law of averages, are subject to possible change as more observations are made in a given deposit or district and as the science of geology itself advances. Just as in salesmanship, employee relations, credit banking, life insurance, and other lines of human behavior, so in mineral engineering it is often necessary to resort to the study of mass action. During and after the recent war, the Bureau of Mines and the Geological Survey developed much new information about pegmatites. It was found that in many cases the minerals occur in definite zones, and that fairly accurate predictions could be made as to the projections of these zones at depth and even as to their probable mineral associations, tonnage, and grade. As a general pattern begins to emerge, scientific studies are likely to increase the percentage of good guesses over bad ones.

Recent technologic trends diverge in two main directions. The better understanding of pegmatite deposits, on the one hand, helps to concentrate activities within the most productive parts. By eliminating much fruitless prospecting and dead work, mining can be more selective. On the other hand, more efficient mechanical methods for separating valuable minerals from one another and from waste make it less important to avoid mixing or diluting the valuable minerals, thus favoring mass mining instead of selective mining and hand sorting.

Mining costs per ton of rock broken can ordinarily be cut in half and often reduced even more drastically, as compared with gopher-hole or other selective mining, when the whole face of a quarry is blasted down and loaded without paying much attention to mixing the valuable minerals or diluting them with wall rock. Further favoring mass mining followed by mechanical concentration is the larger saving of fine sizes and better recovery of small crystals of minor mineral constituents, which could never be separated economically by hand cobbing on the quarry floor. In recent years, it has averaged in the United States at least $2.50 per ton of material mined at mica and feldspar mines by quasi-hand or nonselective methods usually employed. As this figure is a close approximation of the probable cost of both mining and milling by more modern methods, it is easy to see that only a slight increase in yield of merchantable product per ton or rock broken would result in a large increase in profits, provided local conditions are favorable. On the other hand, rough handling incident to mass mining may impair the structure of sheet mica or gems. It may also disintegrate and dilute rarer minerals that occur as occasional large crystals. The latter can often be readily seen and recovered in the pit when mining by hand, but they disappear from sight like the proverbial needle in a haystack when mass methods are employed. This difficulty can be ameliorated only partly by introducing a picking belt in the mill flow sheet.

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Further favoring cheap, rather nonselective mining is the fact that hourly wages in certain rural mining areas in the South have increased as much as fivefold during the last 15 or 20 years. In some parts of the country they have more than doubled. Particularly when the supply of mine labor is not so abundant, today's wage rates make it almost imperative to reduce hand labor to a minimum.

If better understanding of geology can make mining somewhat more selective, so much the better; but, in balance, the major trend is now more and more toward mechanization. It may also be noted that the new methods have already revealed new sources of feldspar and scrap mica in massive rocks. This trend, if it persists, may curtail competitive operations based upon pegmatites. It probably will hasten abandonment of operations on overly small and irregular deposits such as have so largely characterized these industries in the past. Mechanized operations are notoriously inflexible. When expensive equipment is idle or has to be shiften around to accommodate changes in the character of material being mined, costs mount rapidly. Even when grouped together in a multi-unit operation, some pegmatite mines are not well-adapted to extensive mechanization. By and large, however, increased mechanization is likely to result in more regular operation of pegmatite mines, larger units where natural conditions are favorable, higher yields of major constituent minerals, and recovery of more byproduct minerals.

BASIC PEGMATITES

In this report, as elsewhere, the term "pegmatite" generally relates to coarse-grained, acidic rock or what is often called "giant granite." The most abundant pegmatites are fairly rich in quartz and more or less similar in composition to ordinary granite.

It must be recognized, however, that there are pegmatites of basic composition. In such deposits, quartz is absent or present only in minor proportions. Gabbros, for example, are sometimes accompanied by bodies of coarsely crystallized soda-lime feldspar and pyroxene, whereas the pegmatites associated with diorite characteristically carry basic feldspar and hornblende. Corresponding to the anorthosites are pegmatites containing labradorite, hypersthene, and ilmenite. Typical of nepheline syenites are pegmatites composed of soda spar, nephelite, sodalite, lepidomelane, mica, aegerine, arfvedsonite, and zirconium and titanium minerals.

The vermiculite deposits near Libby, Mont., may have originated as basic pegmatites, and the titanium-bearing nelsonite dikes of Virginia have likewise been so classified by some authors. Apatite and rutile are generally more abundant in basic pegmatites than in ordinary granitic types, and the presence of phlogopite instead of muscovite is perhaps characteristic. A number of Canadian phlogopite-pyroxenite pegmatite deposits have been worked both for their phlogopite and apatite content, but relatively few basic pegmatites have ever been important economically. This is partly because the high-lime feldspars are less desirable for ceramic uses than potash or soda spar and also because they are often intergrown with iron-bearing impurities.

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GEOGRAPHIC LOCATION OF GRANITIC PEGMATITES

Pegmatites are widely distributed over the globe and are typically abundant in regions underlain by massive crystalline rocks as distinguished from those characterized by sedimentary rocks or recent lava flows.

The most spectacular groups in this country, famous for their great size and profusion of minerals, are those of the Black Hills of South Dakota, northcentral New Mexico, Latah County, Idaho, and Pala, Calif. Western North Carolina, the principal source of domestic sheet mica, also has furnished some rare minerals. Other well-known sources of rarer minerals, chiefly in specimen quantities, are individual deposits in the mountains of Colorado; in New England, especially in Maine and Connecticut; and around Amelia, Va. Barringer Hill, Tex., another famous locality, was flooded by the Buchanan Reservoir of the Lower Colorado Authority.

In the United States, as elsewhere, the commonest pegmatites are the simple or granitic type. Pegmatites that are at least potential sources of feldspar and/or mica occur in the Piedmont belt across all the Atlantic Coast States and into Alabama; the numerous clusters of deposits, however, are irregularly spaced, and in each district the deposits vary greatly in size, number, and economic importance. In the Western States, pegmatite districts are spaced even more irregularly from the Dakotas to Texas, and also in Idaho and California. Inasmuch as pegmatites are genetically related to granitic rock masses, it is noteworthy that great areas of granitoid rocks along the Sierra Nevada, the Coast Range, the Rocky Mountains, and other western mountains contain no important pegmatites. As might be expected, pegmatites are virtually absent from the Atlantic and Gulf Coastal Plain, the Mississippi Valley, and other regions where the geological formations are mostly sedimentary.

Much of the Province of Quebec north of the St. Lawrence and a large part of Ontario consist of crystalline rocks containing many pegmatite dikes, and commercial feldspar deposits exist in many other parts of Canada. Hundreds of pegmatites have been found in Norway and Sweden, and these countries have furnished most of the feldspar for European potteries. More or less simple pegmatites carrying abundant feldspar are found in eastern Europe, Asia, Africa, and South America. Complex pegmatites richer in rarer elements are found in the Spanish Peninsula, Australia, Africa, Argentina, and Brazil. India and Brazil have been the chief sources of the world's sheet mica and much of the beryl, but mica and other pegmatite minerals have been produced in Madagascar, Guatemala, Mexico, Bolivia, Peru, Ceylon, Korea, New Zealand, and various other countries, in addition to many of those mentioned as potential sources of feldspar.

GENERAL GEOLOGY

Emphasis has rightly been placed in the past on the erratic and seemingly unpredictable structure and composition of pegmatites. Only recently has the work of Government geologists and engineers shown that the distribution of commercial minerals in such deposits is likely to obey certain rules. Although many pegmatites do appear to be essentially massive, being composed of uniform

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mixtures of component minerals, others exhibit a systematic arrangement or zoning. The extent, shape, and trend of the zones that carry commercial minerals thus become controlling factors in mining, exploration, and estimating reserves.

The bibliography of selected references at the end of this paper documents the gradual development of a better understanding of the origin and nature of pegmatites. The literature, however, reveals stormy disagreement among older scientists and marked conflict in major theories relative to the economic geology of these bodies. As a result of the coordinated strategic mineral explorations by the Government during and since the recent war, additional knowledge has been gained which has made it possible to forecast the yield of strategic minerals from many deposits, to measure tonnage reserves, and to obtain other data necessary for planning an orderly mining program. A full exposition of the new concepts regarding the origin and structure of pegmatites and summarizing the studies of geologists of the U. S. Geological Survey is scheduled for early publication. Most of these new concepts, however, have been disclosed in separate reports, notably those listed in the footnote below.3/

Based upon these reports and discussion with several of the authors, the present writer has endeavored to set forth certain essential features of this pioneer work in a later section under the heading "Internal Structure." Although these new concepts are revolutionary, it may be of interest first to review some of the earlier ideas that seem to have been most widely accepted.

Pegmatites have been variously classified according to mineral composition, internal structure, probable origin, or location in respect to an assumed parent granitic body. Most theories of origin presuppose the existence of a pegmatitic liquid charged with water vapor and other volatile constituents. The presence of hyperfusible or "mineralizing" elements and gases in the rock solutions that generated the pegmatites would promote free movement of atoms. This, in turn, would favor the formation of large crystals. It would also explain the fact that such solutions are able to travel long distances, often dissolving additional elements from the intervening rocks traversed. According to the "magmatists", these solutions are products of the differentiation of deep-seated magmas. In some areas, pegmatite bodies show no reasonable relationship to any possible parent igneous rock mass so it is generally conceded that the pegmatitic solutions might come from other sources. Another school of geologists, the "transformists," holds that many large granitic masses themselves did not originate from the consolidation of

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3/ Bannerman, H. M., Structural and Economic Features of Some New Hampshire Pegmatites: N. H. State Planning & Development Comm., Min. Res. Survey, pt. VII, 1943, 22 pp.
Cameron, E. N., Larrabee, D. M., McNair, A. H., Page, J. J., Shainin, V. E., and Stewart, G. W., Structural and Economic Characteristics of New England Mica Deposits: Econ. Geol. vol. 40, 1945, pp. 369-393.
Jahns, R. H., Mica Deposits of the Petaca District, New Mexico: N. Mex. Bur. Mines & Min. Res. Bull. 25, 1946, 289 pp.
Johnston, W. D., Jr., Beryl-Tantalite Pegmatites of Northeastern Brazil: Bull. Geol. South America, vol. 56, 1945, pp. 1015-1070.

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an acid magma but were formed by diffusion or progressive percolation of old, deeply buried rock by hot solutions. Writers of both schools believe that pegmatites were formed by the injection of molten material forced into fractures in older rocks.

A familiar concept is that most pegmatites began as a simple injection of potash feldspar and/or quartz, and that the presence of other minerals in numerous deposits indicates that such deposits were invaded later by new solutions. This theory was introduced by Schaller, Hess, Landes, and others and is described in reports published in 1925 (see bibliography). It was subsequently extended to show that the formation of complex deposits as a result of the replacement of the original granitic composition by a new group of minerals tended to proceed in four possible stages, namely; (1) late magmatic stage (above 600° C.), (2) post-magmatic stage (600° to 400°C.), (3) hydrothermal stage (400° to below 70° C.), and (4) supergene process stage (weathering).

Based upon studies of the order in which minerals formed (paragenesis) in deposits, observers in various districts have concluded that the initial step in high-temperature modification of a simple pegmatite was albitization, that the next step was muscovitization, and that the development of lithium minerals, cassiterite, and sundry other constituents followed according to a more or less typical sequence. Some observers have attached too much significance to the determination of which minerals are more or less perfectly crystallized. The factors that cause one crystal to be euhedral and another subhedral or anhedral are quite complex. On the other hand, it is reasonable to suppose that one mineral is later in its development when it occurs either (1) as a pseudomorph or replacement after an original mineral or (2) as a filling in fractures or cleavage cracks in earlier minerals. It does not follow, however, that the elements composing the later mineral were necessarily injected into the pegmatite mass later than those composing the older mineral.

It is still believed that there are two main stages in pegmatite development, but the new field evidence indicates that the early stage was more complex than previously had been apprehended. In the simplest case, the development of a zoned pegmatite results, in all likelihood, from the deposition of concentric shells inward from the walls of the chamber. The possibility of succeeding hydrothermal replacements in many deposits is not disproved, but in most of the deposits studied the zones were not developed by hydrothermal replacement of pre-existing massive pegmatites.

MINERALIZATION

As many as 50 minerals have been identified in the pegmatite deposits of each of several districts and suites of 30 varieties from a single deposit are not uncommon. Although many of these minerals have no commercial uses, their presence may be of great interest insofar as it may afford a clue to the genesis or structure of a given deposit. Certain species are likely to be segregated in zones or concentric shells.

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Useful minerals that have been produced commercially from granitic pegmatites or from eluvial or alluvial deposits derived from pegmatites include allanite, apatite, beryl and chrysoberyl, bismuth minerals, cassiterite, cesium minerals, columbo-tantalum minerals, cryolite, feldspar, fluorspar, lithium minerals, mica, molybdenite, precious stones, thorium and rare earth minerals, tungsten minerals, and uranium minerals. Magnetite is a common constituent, although ordinarily not in sufficient amounts to be worked as an ore of iron. High-grade kaolins are often the product of alteration of feldspar that originated in a pegmatite. Certain primary or residual kaolin deposits are surface cappings of pegmatite deposits and turn into feldspar or graphic granite at depth. Basic pegmatites have yielded apatite, corundum or emery, titanium ores, vermiculite, phlogopite, and perhaps other marketable minerals.

Although many of the rarer minerals are characteristically found only in pegmatites, only a small percentage of the total number of pegmatites contains more than a half dozen minerals. Simple pegmatites consist essentially of potash feldspar (microcline, orthoclase, or microperthite) and quartz. Although some pegmatites consist almost entirely of quartz and others are almost pure feldspar, simple pegmatites normally contain 50 to 60 per cent feldspar by volume. In addition to potash feldspar and quartz, even simple pegmatites are likely to carry more or less muscovite and plagioclase and often rather small amounts of the common accessory minerals, such as apatite, beryl, garnet, black tourmaline (schorl), chlorite, titanite, magnetite, or zircon. The list of supergene minerals, products of near-surface alteration of weathering are chiefly calcite, kaolin, and iron oxides.

Even when pegmatites grade into veins of massive quartz, they are quite unlikely to contain substantial proportions of sulfide minerals. Except for tin ores recovered in oxidized zones and a few mines that may supply rare elements, scarcely any pegmatites are rich enough in metallic elements to be economical sources of base or precious metals. Ordinary metalliferous veins, especially sulfide veins, are wholly different in origin.

The final stage of weathering occasionally yields high-grade white kaoline, which can be marketed after eliminating the grit by washing and then, if necessary, bleaching. As a rule, however, iron-bearing minerals in the pegmatite or iron salts deposited by surface or underground circulating waters ruin the color and render the clay unfit for high-grade uses. Deeply weathered pegmatites, particularly in the South, where they are often called "flukan dikes," are occasionally worked successfully by pick and shovel mining to recover books of mica. In North Carolina there are several mica operations where the disintegrated material is hydraulically sluiced or loaded by a power shovel and washed, screened, and hand-sorted.

SIZE, SHAPE, AND ATTITUDE

The outline, dimensions, and continuity of many pegmatite bodies is controlled largely by the structure of the older rocks in which they occur. If the older rocks are readily penetrated (e.g., biotite schist), most of the pegmatites are found outside the parent granite mass as exterior pegmatites.

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Conversely, if the older rocks are massive, unsheared, and sparingly jointed igneous rocks, or if the parent granite is relatively well-jointed, marginal pegmatites are more prevalent. When the surrounding rock is well-bedded, pegmatite bodies are likely to exhibit considerable length, parallelism, and regularity in strike and to be more regular in contour downdip. When injected into massive rocks, on the other hand, they are likely to be highly complicated in their geometry and to become more irregular with depth. Even under the most favorable circumstances, all pegmatites may pinch and swell and they may branch or change direction abruptly. Sills usually follow the bedding planes. Dikes and veins also follow the bedding planes or the foliation, but they sometimes cut across.

In a given district, it will often be found that different pegmatite bodies lie roughly parallel, but, especially in crystalline rocks, there are usually others that trend in other directions. Sometimes these erratically disposed pegmatites differ in composition or are smaller or less regular in outline than the parallel ones, but not always. Spherical bodies or cylindrical bodies are not uncommon, and in some districts many of the deposits are characteristically pod-shaped. In New Mexico, for example, the pegmatite bodies, as reported by Jahns[4], are mostly dikes, sills, pipes, or pods, but others have more irregular shapes. He divides them into five classes, as follows:

Class I. Dikes, sills, pipes, and elongate pods.

Class II. Dikes, sills, pipes, and pods with bends, protuberances, or other irregularities.

Class III. Trough- or scoop-shaped bodies with or without complicating branches.

Class IV. Bodies with the form of an inverted trough or scoop.

Class V. Other bodies (including combinations of the above as well as miscellaneous shapes).

Deposits vary greatly in size. They range in width from a few inches to hundreds of feet and in length up to several miles, and the ratios of length to breadth range from scarcely 1:1 to as much as 100:1. They are known to extend to great depths, but often they do not. In large lenses or nearly tabular deposits it is customary to assume that continuity downdip bears some relation to the strike length, but this is not a safe rule to follow. In deposits found at the surface it may be difficult to determine how much vertical depth has been removed by erosion, and in some districts the individual deposits are notoriously shallow. In Namaqualand,[5] for example, economic mineral-bearing pegmatites occur within a vertical range of at least 1,000 feet, but no single deposit in this region persists to anything like that depth. Although sometimes new lenses or other disconnected

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4/ Jahns, R. H., loc. cited.
5/ Gevers, T. W., and others (see alphabetical list of geologic references at end of this paper).

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deposits occur at depth, just as they do along the strike, they may be difficult to find when they do not outcrop.

INTERNAL STRUCTURE

Pegmatites are likely to possess a general orderliness in the distribution of mineralogic and structural units. Occasionally, a distinct banding or zoning is easily recognized, but usually this orderliness does not become apparent without detailed observation and careful mapping. Probably some pegmatites do not follow any set of rules for they seem to be relatively homogeneous or hopelessly jumbled. In any case, however, such rules or characteristic features as may be established, even tentatively, in a given deposit may prove valuable aids to commercial exploration, development, and mining. Concentrations of economic minerals tend to occur in parts of the deposit that can be distinguished from other rock units that are barren.

To show the suitable classification of possible zoning may be economically important, it was calculated by the United States Geological Survey in 1943 that 73 percent of the total wartime output of sheet mica in New England came from wall-zone type deposits, and less than 1 percent from pod- and fracture-controlled types. The remainder of the production came from three other classes of deposits - intermediate zone types furnishing 11 percent of the total, disseminated types 8 percent, and complex and special types 8 percent.6/

In this region, no sharp distinction was noted between barren and productive pegmatites, but the best indication of a good mica deposit was pronounced zonal structure. Recent investigations in other regions have stressed the significance of structural interpretations.

The lithologic and structural units that can be recognized in many pegmatite bodies comprise7/ (1) fracture fillings or bodies (generally tabular) that fill fractures in previously consolidated pegmatites, (2) replacement bodies, formed at the expense of pre-existing pegmatite with or without obvious structural control, and (3) zones or concentric layers that commonly have boundaries roughly parallel to those of the main body. These units are distinguished by differences in composition or texture, or both. The contacts between units may be knife-edge sharp or diffused over several feet of broad gradations, and they need not be at all uniform.

Perfect zoning would comprise a series of concentric shells surrounding an innermost zone or core and would appear to result from development of the pegmatite in successive stages inward from its walls. Although inner zones, or branches therefrom, often cut through outer zones, the reverse relation is unknown. Zoning is not necessarily complete. Partial zoning may develop only along one side or at one end of the body and may exist as lenses, layers, pods, or other forms. There are at least four types of zones. Progressing inward from the bordering wall rock, these zones have been given the following

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6/ Cameron, E. N., Larrabee, D. M., and others, loc. cit.
7/ Johns, R. H., loc. cit.

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descriptive names: (1) Border zones, (2) wall zones, (3) intermediate zones, and (4) innermost zones or cores.

Border zones range widely in thickness and grain size. Sometimes they are sharply defined, or again they may gradually fade into wall rock. A common type consists of fine- to medium-grained aggregates of microcline, quartz, and a little mica, with or without garnet, fluorite, and/or beryl. Another type is a rather thin rind containing a large proportion of mica and probably representing alteration of the wall rock.

Wall zones are generally well-defined but range in thickness from almost nothing to tens of feet. Usually they are composed of coarse microcline and quartz with minor amounts of mica, garnet, fluorite, and beryl. Although more or less graphic granite may be present, these zones are likely to contain giant crystals of feldspar, often bearing well-developed faces encased in quartz, and in places the quartz may form pure masses several feet across.

Intermediate zones are rarely complete and are almost always quite irregular. They are completely absent in some pegmatites, whereas others may contain three or more. The texture is usually coarse, but the composition of these zones has a wide range. The commonest types, however, consist of (a) blocky microcline, (b) coarse graphic granite, or (c) massive quartz with scattered microcline crystals ranging from 6 inches to 12 feet or more in diameter.

Cores are typically composed of massive quartz, occasionally with large but scattered crystals of microcline. However, occasional cores are made up of ordinary pegmatite mixtures of coarse-grained microcline and quartz or even graphic granite. Like the outer zones, the cores of a deposit may have nearly the same shape as the adjacent walls of the deposit, but often they appear merely as long, thin spines or pods or discontinuous lenses. It has been suggested that the quartz veins that frequently occur in the vicinity of pegmatites are probably related to and either contemporaneous with or only a little later than quartz cores of the pegmatites.

Heinrich's conclusions in regard to the pegmatites of Eight Mile Park, Colo.,[8/] were that zones were formed by crystallization of the pegmatite magma in successive stages inward from contacts. Slower cooling and consequent coarser texture in the inner zones may have been aided by the concentration of volatiles in the central parts of the bodies. Superimposed on this zonal structure are secondary units of several types, including fracture-filled veins and fracture-controlled and zone contact-controlled replacement bodies. The guiding fissures for hydrothermal solutions, which caused replacement, are not always visible but often can be discerned. These solutions may represent further additions to the pegmatite from the original magmatic source or merely the offspring of the pegmatite magma itself, accumulated as residual, volatile-rich material during the development of the zones. In the Colorado area, the volume of pegmatite formed by hydrothermal processes is very small, of the order of 1 percent of the total volume in the district. Two phases of hydrothermal action are noted.

8/ Heinrich, E. W. See alphabetical list of Geologic references at end of this paper.

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The earlier is characterized by abundant muscovite and red plagioclase (oligoclase-albite), by less abundant garnet and black tourmaline, and by intense concentrations of apatite, triplite, and beryl. Products of the second phase include lepidolite, cleavelandite, and colored tourmaline.

PROSPECTING AND DEVELOPMENT

Outcrops of pegmatite bodies are abundant in most regions where they occur. As most of the pegmatite constituents are harder and more resistant to erosion than other rocks, their outcrops are often quite prominent and are likely to be found at or near the summits of knolls or ridges. Usually they are striking enough to attract the attention of farmers, hunters, or general prospectors.

In glaciated regions, such as northern New England, the outcrop material is fresh and virtually unweathered. In the South, on the other hand, kaolinization of feldspar and weathering effects may extend to depths of 100 feet or more. Nevertheless, characteristic quartz boulders and occasional books of mica generally help to identify the outcrop even when other signs are lacking.

As part of the strategic and critical minerals prospecting program of the Bureau of Mines during the recent war, consideration was given to extensive prospecting for pegmatite deposits in the Eastern Region. In New England, for example, it was found that observers in a slow-moving airplane, helicopter, or dirigible airship could recognize pegmatite outcrops on the summits of wooded mountains. These outcrops were usually barren of vegetation and distinctly light-colored against the dark-gray wall rocks. In new territory, this procedure might be employed successfully, but most of the New Hampshire mountain tops, which are now difficult to reach through the tangled undergrowth in the steep and rugged side slopes, were open pasture lands half a century ago. Many of the outcrops were known locally at that time, and fairly good records remain in respect to most of those that have ever been worked. In Alabama, where the soil is deeply weathered, it was found possible to develop new prospects by geophysical methods. The quartz ribs or cores characteristic of mica-bearing pegmatites often can be traced by means of magnetometer surveys, even when fairly deeply buried. However, here again it was unnecessary to seek new outcrops, inasmuch as more surface outcrops were available than could be explored at that time. In some cases, however, magnetometer surveys can be employed successfully to delineate possible extensions of known deposits.

Geochemical determinations of nearby rocks, particularly those that may have been derived from a parent magma, may yield scientific information of geologic interest but probably would not help either to find or to guide the working of a commercial deposit. Local enrichment of larger rock masses in certain minor or trace elements often is due to partial pegmatitization, but attempts to correlate chemical analyses of pegmatite bodies with those of nearby rocks are likely to lead nowhere. Occasional investigations in several districts have indicated that enrichment of wall rocks, when it occurs at all, is probably due to impregnation by the same solutions that produced the pegmatite. On the other hand, a good deal can be said in favor

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of careful petrographic and field studies within the pegmatite body itself in order to detect possible zoning.

In seeking new deposits of heavy minerals or even mica, the time-honored arts of the gold prospector may be effective. Careful panning may supplement ordinary visual observation in tracing the source of float material upstream or up a side hill. Given an outcrop that shows evidence of reasonable size and suitable mineralization, careful inspection of the ground will often reveal the probable location of even partly exposed hanging or footwalls. In deep soil a few test pits may be sunk in order to obtain additional information, and the course of the dike or vein can then be determined by cross trenching. Preferably, these cross trenches should expose unweathered material, but frequently a good deal of information can be obtained if weathered material can be found in place. Under suitable topographic conditions, trenches may be cut fairly cheaply with a bulldozer down to 20 feet or more, but, of course, deeper explorations rapidly become prohibitively expensive. In such case, consideration may be given to shaft sinking at one or more favorable points and drifting along in the solid rock below the highly weathered zone.

Having roughly outlined the horizontal extent and zonal characteristics of a deposit at or near the surface, its downward extension can often be determined by prospect drilling, usually core drilling.

These standard procedures quickly develop needed information in respect to a more or less tabular body, but podlike pegmatites and those that twist and turn sideways or up and down may tax the ingenuity of the mining engineer and geologist to the utmost. Often it seems that the only way to obtain information is to keep on digging, but unless this procedure yields marketable products, it is expensive, often prohibitively so.

In deposits valuable only for feldspar, explorations and development that indicate the attitude and general dimensions of the pegmatite body may suffice to demonstrate its economic value with a minimum of actual sampling and chemical analysis. In such cases, experience and careful observation often yield more dependable information than the most carefully compiled engineering data taken at too few isolated points.

The evaluation of deposits for other recoverable minerals is likely to be highly difficult. Little real information can usually be obtained from chemical analyses of run-of-mine samples. Petrographic study of split drill cores and careful hand picking of large samples shot from exposed faces will serve to identify the minerals present, but quantitative information thus obtainable needs to be interpreted in terms of possible zonal agreement. Microscopic grain counts of coarsely ground samples will show even more accurately the relative distribution of minerals present in a given portion of material and are especially useful as a guide to mineral-dressing investigations and as a control of actual milling operations.

To avoid erroneous conclusions, however, due to possible variations in the composition of apparently pure minerals, a considerable amount of analytical chemical work should also be done. The main problem is to determine the

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average composition of minable portions of the deposit, and no single sampling procedure can be generally applicable to all deposits. It may happen that a sample weighing several tons may not even be representative of a section only a few feet away. Good judgment, therefore, may be more useful than meticulous adherence to theoretical sampling procedures. In respect to sheet mica, the physical structure is even more important than the percentage content and estimates of the economic yield should take account of the quality of material encountered in such portions of the productive zones as can be observed.

In districts where zoning has been observed or suspected, it is important to recognize the type of deposit and to plan the prospecting and development as well as mining on the basis of the zonal structure. This information sometimes can be obtained by simple trenching but often requires many openings, careful observation, and detailed mapping before it becomes apparent. Zoning, it should be noted, is three-dimensional. Deposits that may appear to be unzoned at one horizon sometimes show a striking zonal structure at a higher or lower level. The nature of minerals may be a valuable clue. For example, the presence of much potash spar on biotite is considered unfavorable when prospecting for sheet mica, whereas the presence of plagioclase-rich zones along the walls or in an intermediate zone is likely to be a good sign.

The presence of trace elements often is not revealed by chemical analyses. This is particularly true in respect to beryl and may be true in respect to other minerals. Supplementing geologic field work with careful petrographic samples in the laboratory is often indicated. When feldspar and/or quartz are the principal objects of exploration, it is frequently advisable to take samples of the hand-picked, apparently pure minerals and have them analyzed for iron and other possible impurities that may be present as disseminations that may not be otherwise identified. Similarly, it is usually wise to have chemical analyses of samples of beryl, spodumene, and perhaps other minerals that are subject to partial replacement or are likely to occur as pseudomorphs masquerading as valuable minerals although actually more or less worthless.

In respect to mica deposits, there is a widespread fallacy that the quality of the mica usually improves with depth. Mineral stains, mineral inclusions fracturing, and such structural defects as A-structure, herringbone, ruling, etc., however, are no more likely to disappear downdip than along the strike. On the other hand, where books may be water-soaked, mud-stained, or damaged by frost, these effects are likely to disappear within a very few feet from the surface. The same may be said of organic staining or rust stains.

MINING METHODS AND COSTS

Pegmatite deposits have generally been mined on only a small scale by rather primitive methods. Even in the larger operations, hand labor has been employed to assure careful mining and hand selection. The average feldspar or mica mine in 1939 employed less than nine wage earners, and, of course, many operations were much smaller. Substantial contributions also came from farmers, who worked at mining only when other work was slack. Several of the feldspar-grinding mills in the South were supplied by odd lots

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of spar mined and hauled by individuals or family groups from scattered small outcrops.

According to Burgess (Industrial Minerals and Rocks, pp. 269-270):

> The great majority of feldspar mines are open-cut or quarry operations***. A cut is run in or a pit sunk in good float material, or mining is started directly on an outcrop. Hand drilling is done until the openings, together with surface indications, show sufficient feldspar to justify the expense of moving a portable compressor and air drills or running a pipe line from the nearest mine.
>
> Material is moved by wheelbarrow, car line, sled, or motor truck. It is hoisted by windlass, whim, or derrick, or by hoist and derrick. Discarded automobiles have been the boon of the feldspar miner. An old car obtainable for between $10 and $50 provides an engine suitable for hoisting, pumping, or air-compressor drive. Some of these cars are suitable for haulage purposes, usually for waste disposal, and often are operated at a cost saving, even in the South where labor rates are low. At the comparatively few large feldspar-mining operations, more expensive equipment is installed. Stationary power plants and railroads and aerial tramways have been built at some mines. With the advance in efficiency of portable compressors and economy of operation of motor trucks on grades up to 20 percent or more, it is probable no other equipment will be justified in the future even at the largest mines.

Increased mechanization has become a "must" at all domestic mines. However, as foreseen in the above quotation, it has been largely confined in pegmatite mining before and during the recent war to wider use of portable compressors and air drills and better pumps and trucks. Since the war, steadily advancing wage rates coupled with improved milling methods and a better understanding of the internal structure of deposits have encouraged operations on a larger scale. Moreover, in some localities many of the smaller, easily accessible outcrops have been exhausted. As mining operations have grown less highly selective, some attempt is made to maintain a fairly regular quarry face and a clean floor, so that power shovels and larger trucks can be used for loading and carrying away the spar or waste. Instead of hand cobbing and selecting material on the quarry floor, the larger companies have installed picking belts. At one New England operation, for example, the broken rock is loaded by a 3/4-yard power shovel into trucks, carried to a belt conveyor, and then discharged on a 3-inch bar screen. Oversize from this screen goes to a crusher and rejoins the underflow, which goes to a vibrating screen with a 1-inch openings. The undersize of this screen goes to waste, and oversize is hand-picked before shipping. Another New England operation includes a flotation plant that recently has been supplied largely by waste from former mica and feldspar mining. Current mining operations follow the most modern methods, including "ripple blasting," so as to obtain the maximum efficiency from explosives.

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Underground mining of pegmatite minerals has been confined largely to deposits containing well-zoned minerals of relatively high unit value. The world's deepest pegmatite mines are probably in North Carolina and India, and none of them are more than about 500 feet below the surface. In wide pegmatites, open quarries over 100 feet deep are not particularly uncommon; a few are much deeper, but it is doubtful whether any open-cut mine has been operated below about 200 feet. So far as known, no pegmatite deposits have been worked by block caving or other methods of underground mass mining. In narrow deposits, open-cut operations become increasingly difficult and dangerous at rather limited depths, after which the deposit must either be worked underground or abandoned. Underground operations are typically unsystematic. Workings are not planned in advance and follow no regular pattern. They usually wind about, following the "pay streak." Being typically narrow, they require little or no timber except at shaft collars and in shallow workings in the weathered zone.

In the hope that better methods of advance development and sampling and more effective methods of mining, including selective mining, can be devised, the Bureau of Mines has recently undertaken the exploration and development of certain deposits that are being operated as small experimental mines. Results of these experiments will be published in accordance with the Bureau's policy of disseminating information promptly after it becomes available.

The Bureau also contemplates studies of present-day costs at typical commercial mines. In the absence of recent figures, it seems likely that mechanization and other changes in mining techniques have partly but generally not entirely offset higher hourly wages and other concessions to labor since 1939. In the 1930's, with methods then in vogue, it was customary to figure that two man-hours were required to move 1 ton of rock, and that labor represented half the total cost. If wages were 25 cents an hours, as they often were in the South, the labor cost was 50 cents and the total cost $1 a ton of rock. If the rock yielded only 20 percent spar and no byproducts, the cost of the crude spar might be as much as $5 a ton, whereas in another district, where wages were higher but yields greater, the cost of the crude spar might be as low as $2.50. At certain Southern mines recently visited by the writer, it is still possible to produce feldspar at a cost of less than $5 a ton at the mines by hand sorting. In other districts, yields have improved and changes in markets have made it possible to sell a larger proportion of the tonnage mined. By modern methods, it should be possible in most localities even now to move rock for $1 a ton; at the National Lead Co., ilmenite mine, at Tahawus, N. Y., open-pit mining costs were recently reported as being only 38 cents a ton. In contrast, the average cost during the recent war at small-scale domestic mica mines, most of which were partly mechanized, was $2.50 a ton of rock broken.

Flake mica is a joint product of clay washing near Spruce Pine, N. C., and disintegrated pegmatite outcrops in the same vicinity and elsewhere are mined for scrap mica. On hillside locations, hydraulicking has been employed successfully, and in less favorable locations the soft material is dug with power shovels and carried to the washer in trucks.

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MILLING METHODS AND COSTS

Until a decade or two ago, the term "milling" was employed, in respect to the pegmatite mineral industries, only to grinding and pulverizing processes for feldspar and ground mica. Mineral-dressing techniques for purifying or separating the minerals had not yet become commercially practicable. Owing to the rapid strides made in technology, particularly in froth flotation of nonmetallic minerals, within the last few years, it is possible now to effect a reasonably clean separation by mechanical means of every commercially useful mineral found in pegmatites. Several of the new methods have already come out of the laboratory and gone to work in the industries. Others may be classed as emergency tools that are available as soon as economic conditions require their employment.

The basic precept of the ore-dressing engineer, "recover your mineral when free," is applicable to most pegmatite operations. This means that consideration should still be given to hand sorting either on the quarry floor or on a picking belt at the mill. Hand methods are notably effective for recovering small amounts of coarsely crystallized rare minerals. Somewhat similar results can sometimes be obtained with the aid of float-sink or heavy-media separation ahead of fine crushing.

The various mechanical methods at present employed or proposed for recovering the principal minerals or for removing their impurities will be discussed in subsequent sections of this report devoted to the specified minerals. The present section, therefore, aims to show in broader perspective the role of milling technology as applicable to pegmatites in general.

As noted in the preceding paragraphs under "Mining Methods and Costs", hand-cobbing and sorting operations at several feldspar properties have recently been partly mechanized by introducing belt conveyors, crushers, and screening equipment on the quarry floor. Material below about 1-inch in diameter that is thus rejected often contains as much as 50 percent feldspar and perhaps a little beryl and other valuable minerals; however, the tonnage of such material at small mines is often too small to justify the expense of installing suitable equipment for washing and purifying it. Although the ultimate uses of feldspar call for material that is finely crushed (glass-making) or pulverized (pottery and other ceramic uses), whatever beneficiating had to be done has been accomplished only on sizes coarse enough for hand selection. So long as impure fines and larger pieces containing even minor inclusions of objectionable impurities had to be thrown away, only deposits or portions of deposits composed mainly of large crystals of clean spar could be worked economically. Some relief was afforded when graphic granite and other reasonably clean quartz-bearing mixtures, formerly worthless, could be marketed, but until flotation mills were built the wastage at virtually all feldspar mines was appalling. Some of the old mine dumps are being put through the new mills, but much of the material has been spread over roads or hopelessly mingled with waste rock and soil removed in stripping.

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Important steps in the development of pegmatite-mineral beneficiation are outlined briefly below:

Before 1916, batch grinding of feldspar was the rule, but in that year the introduction of air separation made continuous grinding possible, any oversize material being returned, if necessary, for regrinding. About 1930 the development of more efficient high-intensity magnets permitted commercial separation to be made of most iron-bearing materials. Magnetic separation was first employed simply to remove abraded iron from crushing equipment, but later it was used to take out tourmaline, garnet, and even muscovite particles from sand-sized material. This innovation not only increased the number of deposits that could be operated economically, but also helped to create a tremendous new and highly profitable market for feldspar and feldspar and feldspar-quartz mixtures in the glass industry.

Inasmuch as magnetic separation cannot be conducted economically on material much finer than about 100-mesh, froth flotation has been adopted at several mills. Using simple reagents in an acid circuit, it is relatively easy to eliminate almost all iron-bearing impurities from a feldspar mixture by froth flotation. Since this process is applicable to exceedingly fine material, it allows separations to be made in size ranges in which locked grains are reduced to a minimum and so can produce a high-grade product from material that formerly had no value whatsoever, including granitic rocks that are virtually not pegmatized at all. A disadvantage, of course, is that the material is wetted, and the cost of necessary drying is a factor.

The next step in the flotation recovery of pegmatite mineral mixtures was the discovery of suitable reagents for separating feldspar and quartz. This is readily accomplished by either soaps or cationic reagents. With the latter type, quartz floats selectively in slightly alkaline pulps; but with acid pulps, especially those containing hydrofluoric acid and laurylamine hydrochloride or amine collectors sold under trade names, the feldspar floats first.

Beryl or spodumene, if present, should generally be recovered before the feldspar. Both minerals can be floated selectively by soap reagents with fluorine ions and/or strong dispersing agents. On some ores, drastic scrubbing and washing are necessary, however, to remove surface alteration products and prepare the mineral particles for selective filming with the proper reagents. Beryl and spodumene have been separated by selective flotation in the laboratory, but with difficulty. As the latter mineral is somewhat heavier (sp. gr. 3.15 vs. 2.7), gravity separation is often feasible.

To avoid the slight complication of an iron-removal flotation step, it may be possible to devise a commercial counterpart of the laboratory method of eliminating iron abraded from machines (and perhaps magnetite, if present) by inserting a magnetized iron rod in the conditioning unit or in one or more of the flotation cells. To reject troublesome iron-bearing minerals that do not float readily, it may be necessary to employ high-intensity magnets to clean up the products after or before flotation. As this process works only on dry material, it involves complications when used as an adjunct to flotation or any wet concentrating process.

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For recovering scrap mica, a variety of interesting possibilities exist. When mixed pegmatite ores are treated by flotation, mica flakes can be taken out immediately after the iron-bearing slimes; if not marketable as ground mica, they are often rejected with these slimes. Alternatively they can usually be removed ahead of froth flotation by means of a scalping screen. Commercial mills recovering scrap mica as a major product have hitherto been based mainly upon alternate crushing through rolls and screening at progressively smaller mesh size. The relative elasticity of the mica books resists size reduction, whereas other minerals crumble and pass through the screens. Replacement of rolls by a hammer mill or other percussion-type crushing device unlocks the minerals at somewhat coarser sizes, minimizes breakage of the mica, and might simplify the flow sheet, but commercial machines of this type are not designed to handle such highly abrasive minerals without rapid wear. Separations based upon differences in particle shape may be successful on fairly large mica books as well as on small flakes. At coarser mesh sizes, alternating rectangular- and square-mesh screens may be used, and various vibrating devices for effecting particle shape separation between tabular or flaky mica and blocky minerals warrant careful investigation. In clay washing in North Carolina jigs and wet shaking tables in which the mica flows across the riffles while sand travels to the "concentrate end" have been supplemented and in part superseded by froth flotation. Air separation or wet classification in either rising or flowing currents has been commonly employed to recover or remove mica from clay slips or finely ground mineral pulps. Air tabling has been used successfully and enables separations to be made between thin leaves or flakes and undelaminated mica particles. Mica can also be winnowed out from most associated minerals electrostatically.

Heavy-oxide minerals, such as cassiterite and columbo-tantalite, can be removed by gravity. Jigs or shaking tables generally have been employed, but where the proportion of heavy minerals is quite small, they are not always desirable. Stationary tables (e. g. the "Sullivan deck") might prove more effective when the material is quite fine or the Humphreys spiral when recoveries can be made on sizes substantially coarser than about 200 mesh. These machines may be inserted in the grinding circuit or perhaps employed on the tailings from the flotation machines.

It is theoretically possible to make gravity separations of the silicate minerals by refined sink-float methods on sizes coarser than, say, 1/4-inch. However, the true specific gravities of several of the pure minerals are close together, and the apparent densities tend to overlap owing to possible voids and disseminated inclusions as well as locked grains. Pure quartz has a specific gravity of 2.65 and thus lies between feldspar (about 2.6) and beryl (usually 2.65 to 2.70, sometimes as high as 2.80). Spodumene is definitely heavier (3.15), and of course tin, tungsten, tantalum, and other metallic oxide or sulfide minerals as well as garnet, tourmaline, and a few other undesirable impurities are much heavier.

Milling costs will vary greatly according to the complexity of the flow sheet as well as the size and location of the operation. Since 1939, they have risen greatly in some localities, not so much in others, and present-day estimates are fraught with many uncertainties. The simplest type of feldspar treatment calls for crushing, drying, screening, and magnetic separations that

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reject fines under about 200 mesh if they are too dirty. For such an operation, involving 200 to 500 tons a day, a rough figure of $1.25 per ton of feed can be assumed. Using flotation merely as a means for removing iron minerals would increase the milling cost per ton to around $1.50 owing to the necessity of drying, but the increase could perhaps be offset by a better yield from the minus 200-mesh flotation. If beryl is to be recovered, the reagents used for eliminating iron-bearing slimes have to be removed and new reagents added, so that the cost of beryl flotation would add another 50 cents per ton, perhaps, to the foregoing $1.50. Feldspar flotation, using laurylamine, a very expensive reagent, might boast the total milling cost up to $2.75 per ton of crude ore treated.

Capital costs, again, are highly variable and likely to change, but for a complete milling operation a reasonable guess is that they will be somewhere around $750 a ton daily capacity on the basis of the foregoing flow sheet, using principally flotation. Many mills have cost much more. On the other hand, under favorable circumstances, by cutting corners and using second-hand equipment wherever possible, it might be possible to come out with a lower average figure.

GENERAL ECONOMIC CONSIDERATIONS

The record shows plainly that the largest pegmatite mines and the only ones that have operated more or less steadily have been feldspar producers. Mica and other minerals may be important byproducts, at times even a main product, but in the past the bread-and-butter business year after year has usually been feldspar. Regular sales of scrap mica, spodumene, or other major product would exert a similar stabilizing influence, but for many years the demand for feldspar has been dependable and growing, and the feldspar-rich zones are characteristically the largest and most persistent parts of a deposit. Recently, more attention has been given to minor elements and to the recovery of joint products. Aided by a better understanding of the nature of pegmatite bodies and better methods for recovering the values, future prospects of any proposed pegmatite enterprise can now be evaluated on its individual merits regardless of past performances or previous mistakes.

In final analysis, any commercial mining venture that does not make money is a failure. Moreover, successful mines should not only pay back the original investment in land, buildings, labor, and supplies, but in the long run they should also show profits comparable with the risk. Under the most favorable circumstances, a large percentage of mining prospects will never pay back the money put into them. Consequently, those that do pay should carry the losses inherent to the business as a whole. Insurance premiums, similarly, are collected from people who never have fires, otherwise it would be impossible to meet the claims of those who do. As no one can pick the winning number every time, the true measure of success or failure is the balance between gains and losses over a sufficiently long period and covering a sufficiently large number of chances. Unfortunately, there is no safe rule for calculating the risk factor, yet it is there so long as successful mines must bear the burden of marginal ventures and fruitless prospecting.

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Any type of mineral engineering project should be examined stepwise, in orderly fashion. Engineering methods of analysis ordinarily follow a more or less standard pattern, which has been phrased in general terms by Fish[9] approximately as follows:

1. Conception of a human need (as evidenced by a probable market).
2. Research, analysis, and planning a project to supply need.
3. Valuation of the project.
4. Organization and promotion of the project.
5. Design of mechanism to carry out project.
6. Construction of the mechanism.
7. Operation of the mechanism.
8. Maintenance and inspection of the mechanism.
9. Sale and distribution of the product.

The application of most of the foregoing factors obviously requires no special comment. Although pegmatite mining has its special problems, it is influenced by most of the factors that affect the economics of any mining venture. Assuming, for the moment, that a demand for a particular mineral seems assured at a given price and in sufficient quantity, the primary emphasis, therefore, is on purity, volume, and cost of product or products.

Often the dominant factor is the location or "place value" of a deposit. Commercial geography, however, is not static. As new consuming outlets develop, as older deposits are depleted, or as access roads are built, hitherto worthless prospects and mines that once were remote from markets or that were abandoned for other reasons often become valuable. Deposits that could not be worked profitably in former years may warrant reconsideration by reason of present-day (1) improvements in mining methods, (2) better separation technology, (3) better understanding of geology, (4) higher prices, (5) larger and steadier demand, or (6) more favorable transportation costs relative to older mines. Inherent to the nature of a given pegmatite body are such additional factors as (7) size, shape, and attitude of the deposit, (8) quality of the principal minerals (finely disseminated or dispersed impurities may render them unsalable even when carefully concentrated in commercial size ranges), (9) quantity of principal salable mineral or minerals, (10) number of other economic minerals present, if any, as potential byproducts, and (11) ease of separation.

Hitherto, pegmatite mining has suffered the numerous disadvantages of a small-scale industry. Individual mines or quarries employing more than a dozen men or producing as much as $20,000 worth of annual product have been relatively few; in the census tabulations for 1939, only four feldspar companies and no mica mines reported products worth over $50,000. Operations that produced less than $2,500 worth of products or spent less than this amount for usual operating expenses, buildings, or equipment are not included in the census figures but such small operations contribute a significant tonnage of pegmatite minerals. As shown in the following table, however, even the Census records reveal that the average pegmatite operation is much smaller and less efficient than unit establishments in other mining industries:

9/ Fish, J.C.L., Engineering Economics, 2d ed., New York, 1923, pp. 3-4.

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Comparative statistics for pegmatite (feldspar and mica) and certain other United States mining operations (calculated from U.S. Bureau of the Census data for 1939)

	Feldspar	Mica	Iron Ore	Copper Ore	Crushed Stone
Total number:					
Operating companies.....	47	22	100	35	1,184
Mines.....	59	21	177	51	1,533
Average per mine:					
Tons product (2,000 lb.)	4,070	985	327,000	1,020,000	85,000
Value of all products...	$16,600	$15,600	$850,000	$2,780,000	$66,300
Persons engaged.....	10.2	10.5	126	523	22.4
Wage earners only.....	8.7	9.1	114	468	20.1
Average per wage earner:					
Value of products:					
Annual total.....	$1,920	$1,720	$7,500	$5,950	$3,280
Per man-hour.....	$0.96	$0.91	$3.95	$2.76	$1.63
Hourly wages.....	$0.38	$0.33	$0.71	$0.67	$0.50
Tons per man-hour.....	0.24	0.057	1.51	1.3	2.1
Horsepower rating of available equipment 1/.	11.1	8.9	28.5	31.6	31.1

1/ Includes power shovels, tractors, and trucks as well as stationary and portable machinery and equipment.

The average efficiency of smaller mines, such as were not included in the foregoing tabulation, undoubtedly was less than the average for the larger properties. Conditions vary greatly, however, in different parts of the country. Most of the production of both feldspar and mica in 1939, as in other years, came from low-wage areas, but production is growing in the Western States, where pegmatite mines must compete for labor with metal mines. Whereas, in North Carolina the average feldspar miner produced only 0.156 short ton of crude spar for a wage of 28¢ per hour, the average output in Colorado during the last prewar census year was 0.415 ton per man hour, and the wage was 53¢.

Mechanization played a part in this picture but is by no means all of it. The average rating of available equipment per wage earner of only 8.2 horsepower in North Carolina compares with 31.8 horsepower in Colorado. The latter figure compares favorably with the average for the more highly mechanized mining industries. As it costs more for the long haul from Colorado to eastern consuming markets, the average reported value of Colorado feldspar in 1939 was only $3.68 a long ton, f.o.b. mine, as against $5.29 for North Carolina spar. The Colorado deposits are generally larger and easier to work; in fact, many of the North Carolina deposits are not big enough to benefit from highly mechanized operations.

The mineral industries as a group have been remarkably successful in overcoming the handicaps of steadily rising wages, deeper workings, and leaner ores, but the technologic developments that have enabled operators to keep down costs are based chiefly upon mass production. The plight of

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the small miner has become steadily worse. This is notoriously true of metal mining and at least equally true of pegmatite mining. The history of virtually every mica and feldspar producing district in this country shows that most of the mines have been worked intermittently by a succession of different operators. Even those that have been most productive have been idle for long periods. Lack of sufficient capital is a common difficulty, but fluctuating markets and numerous other causes enhance the hazards of a small enterprise. The same dike may be mined solely for one mineral at one time and for another mineral later. Products for which no apparent market existed at the moment were usually consigned to the dump. At a typical mine, operations may be suspended or abandoned when the operator goes broke, gets sick, dies, loses his lease, runs into legal trouble, or simply gets discouraged. Lacking the means for making reasonable estimates as to tonnage reserves or even as to the general trend or continuity of the "ore shoots," any operation proceeds from hand to mouth. When mining and prospecting proceed blindly, long-range planning is out of the question.

Wherever mining ventures are typically small and undertaken with too little capital, or where exploration and advance development are customarily either neglected or fail to afford dependable information, methods of mining and the handling of products are bound to be inefficient and wasteful. Another common complaint is that many pegmatites are so small that the life of a single mine is limited to a few months or years when actively exploited. And finally, even when the nature of the deposit is appreciated by the operator, he may still have to concentrate his activities in the richest parts of the deposit, thereby "picking the eyes out" of the mine in order to meet expenses, to make the most of a brief period of high prices, or to get out as much as possible before his lease expires.

Absentee owners too often suffer from high-grading. As in many western mining camps, men who would never dream of stealing other kinds of property often adopt the attitude that "finders are keepers" in regard to minerals found in the muck pile or in the face after a blast. Sheet mica and possibly other products, in addition to gem stones, are valuable enough so that small amounts carried away in dinner buckets or concealed in clothing may convert an otherwise profitable venture into a losing one. It is reported that in India as much as 2.4 pounds of mica was stolen or illegitimately produced for every pound mined and marketed through regular channels. The situation in other countries is probably nearly as bad but is not so readily measured statistically.

Fluctuating markets have been another hurdle for the pegmatite miner. The demand for most rare minerals is notoriously variable and easily saturated. In unmechanized mines it is usually possible to stop mining feldspar and to start mining mica or vice versa merely by moving men from one part of the deposit to another. When operations are mechanized, however, this may still be possible, but it often involves more costly interruptions. The ideal condition for mass mining and milling is a steady flow of uniform material. Under these circumstances it may be necessary to accumulate certain byproducts over long periods when demand is slack. Forecasting demand in a thin market is traditionally hazardous, and the most careful forecasts of anticipated sales are likely to prove fallacious when confronted with a sudden flood of

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imports, bonanza discoveries in competitive mines, or substitution or collapse of a dominant end use. These hazards are superimposed on the ever-present possibility of a disappearance of the erratic enrichment in the mine itself.

The economic backgrounds of pegmatite minerals are summarized on later pages of this report, but it must be kept constantly in mind that economic facts are not static, that the delicate balance between supply and demand, as measured by prices and market acceptance, is constantly subject to change.

FELDSPAR

Commercial feldspars are mostly intergrowths of at least two species. Potash spars consist chiefly of orthoclase or microcline ($KAlSi_3O_8$) but are almost always **perthitic,** which means that they are interlaminated with albite ($NaAlSi_3O_8$). Soda spars, although consisting mainly of albite, usually contain at least a little potash spar and more or less lime spar (anorthite, $CaAl_2Si_2O_8$). There is a series of soda-lime feldspars called plagioclase, ranging in composition from albite through oligoclase, andesine, labradorite, and bytownite to anorthite. Graphic granite (Schrift-granit) or corduroy spar is an intergrowth of feldspar and quartz common in pegmatites; the characteristic structure is banded, and the ratio of feldspar to quartz is usually 3:1.

Orthoclase is monoclinic, but all other principal feldspars, including microcline, are triclinic. The whole group has the same hardness (6 to 6.5), but the specific gravities of pure minerals range from about 2.5 for orthoclase to 2.6 for albite and 2.75 for anorthite. Albite has the lowest melting point (1,110° C.); pure potash spar melts at only a slightly higher temperature (1,200° C.), but anorthite is more refractory (m.p. 1,532 C.). All feldspars may be pure white or even colorless but are often tinted and occasionally fairly strongly colored. According to the writer's observation, pink or yellow coloration (excluding iron staining) may be somewhat commoner in potash spar, whereas albite is often chalk white, and lime-soda spars tend to be gray to blue or green. However, amazon stone, an almost pure variety of microcline, is a fine green, and no general rule can be established in regard to color.

Cornwall stone is a natural mixture of feldspar, quartz, and kaolinite. Kaolinized graphic granite, often blended with a little fluorspar, is marketed as Carolina stone. Aplite is mined in Virginia and is competitive with feldspar, although sold at a lower price. Nepheline, (which usually approximates the composition $K_2Na_8Al_8Si_9O_{34}$) is a feldspathoid mineral and is widely employed for the same uses.

The alumina content, important especially in glass making, ranges from 18.4 percent for potash spar to 19.5 percent for albite and 36.7 percent for anorthite. Pure orthoclase contains 16.9 percent K_2O and pure albite 11.8 percent Na_2O, but commercial potash spars rarely contain over 12 percent K_2O, and most so-called soda spars contain at least half as much potash as soda.

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Identification. - It is frequently desirable to distinguish feldspar and quartz grains in small sand sizes, such as are produced in milling operations. The method used in preparing material for microscopic grain counts in a Bureau of Mines laboratory, according to Dr. Alton Gabriel, is to treat the material first with HF vapor. This treatment leaves the quartz grains colorless but turns feldspar grains a milky white, so that they are readily identified. To distinguish between potash spar and soda or soda-lime spar, this material, after the HF treatment, is immersed in sodium colbaltinitrite. This reagent forms a yellow precipitate on potash spar but leaves other varieties milky white.

Various organic dyes, including one known as safranine, have also been recommended as selective staining agents for feldspar in the presence of quartz, which remains unaffected. After staining, the material can be examined with the naked eye, a hand lens, or under a microscope.

Occurrence. - About 60 percent of all igneous rocks are feldspars. Although granitic pegmatites that would yield large crystals have hitherto been the principal source of commercial production, other occurrences, including massive rocks, are also coming into the picture as modern milling methods are introduced. However, feldspar is the main constituent of most pegmatities, and feldspar-rich zones are usually the largest and most persistent.

Although the portions of a pegmatite that contain the most mica are generally not so rich in feldspar, high-grade deposits of both minerals are virtually restricted to well-zoned pegmatites. Commonly, the commercial feldspar deposits form cores in potash-rich bodies, but some pegmatites contain potash-rich cores enveloped in plagio-clase-rich zones, one or more of which may be a productive mica deposit.10/

Some unpegmatized granites contain as much as 60 percent microcline in the form of fairly coarse crystals. Unfortunately, however, petrographic examination and chemical analysis often show that these crystals are shot full of disseminated particles of iron-bearing minerals, which render the spar worthless for most commercial uses. It is theoretically possible, on the basis of their respective ionic radii, for ferric iron to replace alumina in the feldspar lattice. Ordinarily, however, petrographic examination will reveal that the feldspar crystals are contaminated and that the iron content is carried by discrete famic mineral particles. Whether these particles are separable depends whether they are more or less finely disseminated. Another limitation on the number of massive igneous rock deposits that can be utilized as commercial sources of spar is the fact that in the general run of such rocks a considerable proportion of the feldspar consists of anorthite or other lime-rich, refractory varieties of the mineral.

Uses. - Feldspar is employed principally as a fluxing agent in glass, pottery, porcelain, enamels, tile, and other ceramic products. It is also

10/ Bannerman, H. M., and Cameron, E. N., The New England Mica Industry: Am. Inst. of Min. and Met. Eng., Tech. Pub. 2024, Mining Technol., May 1946, p. 8.

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used rather extensively in scouring soaps and other cleaning compounds; being slightly softer than quartz abrasives, it does not scratch glass. Minor uses include poultry grit, roofing granules, "pebble-dash," and facing for concrete and other "cast-stone" products designed to resemble granite. Coarsely ground feldspar was advocated for extinguishing magnesium incendiary bombs during the recent war, and finely ground material has been used as a flue-dust arrester, as a filler for various products, and in foundry facings. A small tonnage of quite carefully selected crude material is consumed annually in the manufacture of artificial teeth, a ceramic use requiring premium-grade material.

Feldspar gems are found only in pegmatites but are not likely to be encountered in those worked primarily for commercial spar. They usually occur in linings of cavities or vugs. The best-known gems having the composition of feldspar are moonstone, iridescent labradorite and handsome green amazon stone.

Glass spar is used principally in the manufacture of containers, but it is also used in window glass. In the ceramic industry, feldspar is employed both in the body and the glaze. Formulas vary greatly, but typical earthenware batches contain 10 to 15 percent feldspar, vitreous wares 35 percent, and various porcelain products as much as 50 percent.

During the last 20 years or more, 90 percent of the apparent supply of crude spar (domestic production plus imports) has been marketed by merchant mills as ground spar. In 1946, almost 62 percent of the spar sold by merchant mills went to the glass industry, nearly 33 percent to pottery makers, and not quite 5 percent to enamelware manufacturers, leaving less than 1 percent for other uses, chiefly soaps and abrasives. The tonnage shown for glass-making alone that year hit an all-time record considerably higher than total consumption for all purposes in any prewar year. In 1937, 51 percent of domestic sales were for glass-making, 37 percent for pottery, 9 percent in enamels, and 3 percent for miscellaneous purposes. Owing to large expansion of the pottery industry and some contraction in the glass-container industry in 1947 and 1948, the latter distribution may prove to be the postwar pattern percentage-wise, although tonnages are much greater than ever before. In 1913, only 1 percent of the quite small consumption was in glass; 76 percent went into pottery, 9 percent into enamels, and 14 percent for miscellaneous uses.

Production and domestic consumption. - Feldspar is mined in 25 or more countries, but ordinarily the United States produces about twice as much as all other countries combined. The domestic output of crude spar rose from 24,821 long tons in 1900 to a peak of 210,811 tons in 1928. Owing to the Great Depression, it did not rise above 200,000 tons again until 1936, but in 1941 it exceeded 300,000 tons, and in 1946 it rose to an all-time record of 508,380 long tons, but dropped to 459,910 in 1947. Imports in recent years have amounted to somewhat over 16,000 tons, which is less than the 1925-29 average of 28,029 tons annually, corresponding to 12 percent of the apparent domestic supply during that period. Almost the entire Canadian production used to be shipped to the United States in crude form for grinding in American mills.

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Exports of feldspar are not recorded separately but are known to be small. Apart from over-the-border shipments from Canada to nearby grinding mills in the United States, the main international movement of feldspar has been in Europe. Norway and Sweden are relatively large exporters. However, feldspars are so widely distributed and prices are so low that most consuming countries are able to supply their needs locally. Imports of Cornwall stone into the United States from England are no longer important, but those of Canadian nepheline syenite have increased greatly, having amounted in 1947 to 54,382 short tons valued at $194,283.

Marketing. - Although the number of grinders that mine their own spar, either themselves or through affiliated firms, is increasing, most crude spar is still mined by small operators and sold to merchant mills. These mills are preferably situated near the mines or where milling-in-transit freight rates favor shipments to more than one consuming center. Several mines or localities often contribute to the raw-material supply of a given mill, shipments from various sources usually being stock-piled separately and subsequently blended to maintain the desired composition of finished product. A few pottery and enamel manufacturers buy crude spar and grind it themselves. Certain makers of soaps, cleansers, and sweeping compounds likewise mine or purchase crude spar. Sales of crude spar are almost never made through brokers.

Grinding mills. - Except for the small amount sold to the soap manufacturers and large enameling plants, virtually all of the feldspar mined in North Carolina and Virginia is ground in the Spruce Pine, N. C., district, at Erwin, Tenn., or at Bedford, Va. Georgia spar also is ground locally.

Mills in Maine, New Hampshire, and Connecticut, as well as in the vicinity of New York City (Bedford, N. Y.) process local spar, although a little New England crude spar is still ground in Trenton, N. J. Canadian spar is mostly ground in Rochester, N. Y. Grinding establishments in California, Arizona, Colorado, and South Dakota are supplied by nearby mines. Colorado mills, however, supplement local supplies by grinding Wyoming spar and sometimes South Dakota spar. Wyoming spar is also ground in South Dakota mills, and some South Dakota spar is ground by a sanitary-ware manufacturer in Illinois. Ground spar is sold by merchant mills directly to industrial consumers.

Specifications. - No definite standards exist for crude spar, but a relatively simple classification submitted by the National Feldspar Association in N.R.A. days (1933) has received some acceptance, based upon chemical composition and fineness of grind.

The better-quality crude spar in a given district is commonly classified as No. 1, and that carrying more free quartz is designated No. 2. Any material carrying more than about 25 percent quartz or which is badly iron-stained, if salable at all may be called No. 3. Both No. 1 and No. 2 spar should be sufficiently free from iron to burn to a good white color, free from specks. In one district, a product containing as much as 10 or even 15 percent quartz may be classed as No. 1, whereas in another district this grade must be almost free from quartz. Dental spar is the highest-quality selected pure potash spar crystals; it commands a high premium but is marketed in very small quantities.

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For glassmaking, granular or semigranular (usually minus 20-mesh and preferably free from dust) spar is prepared, low in iron (preferably not over 0.08 percent Fe_2O_3); it is desired mainly for its alumina, which is higher in soda spar. Inasmuch as soda is at least as acceptable as potash, and for other reasons, nepheline syenite likewise is coming into wide use. It is worth more per ton because it carries more alkalies and more alumina. In pottery spar, however, the potash-soda ratio is very important. Too much soda is undesirable for most ware and cannot be tolerated for high-tension electrical porcelain or floor tile; even for general whiteware, twice as much K_2O as Na_2O is required. For making pottery glazes, on the other hand, a high-soda spar as low as 1:1 is generally specified. Low iron and good fired color are important in all pottery spar, and the top limit of 20 percent free quartz is much reduced for better grades of ware. Pottery spar is fine-ground; 200-mesh material is specified, but most of it passes 325 mesh. Enamel spar receives an intermediate grind, usually 140-mesh, although all grindings from 20 to 200 mesh may be specified; in this industry, emphasis is placed on uniformity of composition and high potash content.

Abrasive-wheel makers may take 20 to 25 percent free quartz but not over 3 percent Na_2O, and scouring-soap makers, too, want high-potash spar as a rule, although they are not so particular about mica as is the glass or ceramic trade. Mixed products carrying much quartz or more than traces of other mineral impurities are difficult to sell, although they may be used for roofing granules, concrete aggregate, stucco, poultry grit, and miscellaneous abrasives and fillers.

Prices. - Although feldspar producers have benefited by the largely increased demand for their products, prices have remained almost unchanged, whereas wages and other costs have risen sharply.

Quotations for crude spar do not appear in the trade press, and computations based upon sales reported annually to the Bureau of Mines by operators reflect changes in the relative proportions of various grades as well as distance from markets. These factors have more effect upon the averages than year to year changes in the price of any single grade. According to earlier standards, the average feldspar produced today is low-grade largely as a result of including substantial proportions of quartz. Increases in freight rates and changes in freight-rate structure have altered the relative values of feldspar mined in various parts of the country. Notwithstanding these discordant factors, however, it is interesting to compare average realizations from sales of crude spar for the whole country and for leading States in 1947 with prewar figures:

The average value of all crude spar shipped from domestic mines in 1947 was $5.25 per long ton, compared with $4.39 in 1939. Averages per ton for certain States in 1947 and corresponding prewar figures (1939 in parenthesis) follow: North Carolina, $4.88 ($5.18); Virginia, $6.27 ($5.41); Maine, $5.77 ($4.10); Connecticut, $6.50 ($5.31); Colorado, $5.00 ($3.59): South Dakota, $4.83 ($2.77); and Wyoming, $4.79 ($3.72).

Similarly, in the case of ground spar, average realizations from all domestic sales are not strictly comparable for various years. In fact, the

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influence of much larger sales of the cheaper glass spar is even greater for ground spar than for crude spar, owing to the wider spread in value of the ground products. The average sales value of ground spar shipped by merchant mills in the United States was $12.15 per short ton in 1947. This compares with $11.04 in 1939 but is less than the 1935 average of $13.30. Average realizations for individual States ranged from $9.23 to $17.43 in 1947, as against $6.42 to $18.01 in 1939. For specified States, the 1946 average values (1939 in parenthesis) were as follows: California, $8.11 ($6.42); South Dakota, $9.58 ($6.88); North Carolina-Tennessee, $10.57 ($12.15); and Maine, $15.90 ($12.68).

According to the E & M J Mineral and Metal Markets, prices per short ton of various grades of ground spar were as follows in December 1948, f.o.b. North Carolina: potash and soda spars in bulk, 200-mesh; white, $18.50; granular glassmaker's spar, 20-mesh, white, in bulk (#17 grade), $12.50; semigranular, $12.50. Corresponding figures f.o.b. Virginia mills were: No. 1, 230-mesh, $18.50; 200-mesh, $17.50; No. 17 glassmaker's spar, $11.75; No. 18, $12.50; enameler's spar, $15 to $17.

Except for an increase of $1.50 per ton of pottery grades in 1947-48, these quotations are virtually the same as prewar.

Mining and treatment. - The principal features of feldspar mining and milling have been described on previous pages of the report under appropriate sections covering operations on pegmatites in general. Inasmuch as feldspar is the main constituent of most pegmatites, additional comments relate chiefly to segregation of the mineral from associated impurities or other minerals and preparation of the material for market.

Hand-cobbing and sorting still account for much of the total output and are often employed for eliminating bulky impurities, byproduct minerals, or a selected product such as ceramic or an enamel-grade spar before fine crushing, even when mechanical separation is employed. At most grinding mills, the small lump material, until charged to the crusher, is handled by forks instead of shovels, thereby rejecting fines (under 1/2 inch), which are likely to be contaminated.

The simplest flow sheet, employed at several mills operated by one of the largest companies, is designed to produce only glass spar. Following reduction in a jaw crusher to about 3/4 inch or less, the material goes first to a rotary drier lined with silex blocks and then to a double-deck screen, which produces a finished undersize. The lower deck may have an 18-mesh screen set at the proper angle to produce finished material passing 20-mesh. Sometimes, however, a second screening and a slightly coarser mesh is introduced to check oversize in case of damage to the main screen. The upper deck of the screen merely reduces wear on the lower-deck cloth. Oversize from both decks passes through one or more Symons short-head, fine-bowl crushers and returns to the same vibrating screen, thus closing the circuit. A magnetic pulley may be employed to remove tramp iron and abraded metals from the machines. Owing to the high ratio of reduction and the extraordinary fineness of the product, the cone crusher requires special attention. Granularity of product is obtained by employing a large and carefully regulated

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circulating load. If operated empty, the manganese steel linings of the mantle are likely to warp. Capacity of a 3-foot cone at a Virginia plant is reported as being 4 tons an hour, and grinding costs at similar plants are on the order of $2 a ton.

Many dry-grinding plants are designed to furnish either glass spar (20-mesh) or fine-ground material, or both. A typical flow sheet is shown in figure 1.

Flow sheets of various operating mills, giving details of equipment, may be found in several Bureau publications.11/

High-intensity magnets are usually inserted in the foregoing flow sheet to eliminate iron-bearing minerals such as biotite, garnet, tourmaline, or even muscovite. A small amount of additional beneficiation may be accomplished as a result of differential grindability of associated minerals, whereby much of the coarser mica may be separated by suitable throw-out devices.

Until recently, probably at least 50 percent of the feldspar in rock actually broken at pegmatite mines was rejected at the mine dumps or at the grinding mills. Virtually all spar was thrown away before it got to the mill unless it could be loaded with a fork. To eliminate this waste and to make available new sources of feldspar production, the Bureau of Mines made laboratory tests in the 1930's on feldspathic rocks from various parts of the United States. A commercial pilot mill employing froth flotation was initiated at Keene, N. H., and operated successfully, although intermittently, for several years before being replaced, in 1947-48, by a new and modern plant at a better location. The Consolidated Feldspar Corp., after operating a flotation unit for several years at Erwin, Tenn., built a much larger plant at Kona, N. C., which came into production in 1945. Another flotation plant was constructed a year or two later at Spruce Pine, N. C., by the Tennessee Mineral Products Company. Although other methods have been tried for separating feldspar from quartz, including various electrostatic and allied processes, froth flotation has been the most successful. Like all wet methods, it suffers from the disadvantage that the product subsequently has to be dried. As flotation generally is most successful on material finer than about 60 mesh, considerable experimenting was done in the Bureau's laboratory with agglomerate tabling for coarse or sand sizes. Good results were obtained in the laboratory, but this process has not been used in commercial feldspar mills, which have been able to treat successfully all sizes under 20-mesh by straight flotation.

11/ Guiteras, Jos. R., Mining of Feldspar and Associated Minerals in the Southern BlackHills of South Dakota: Bureau of Mines Inf. Circ. 7112, 1940, 104 pp.
Burgess, B. C., Methods and Costs of Milling Feldspar at Minpro Plant, Tennessee Minerals Products Corp., Spruce Pine, N. C.: Bureau of Mines Inf. Circ. 6488, 1931, 22 pp.
Ladoo, R. B., Feldspar Mining and Milling Near Keene, N. H.: Bureau of Mines Report of Investigations 2396, 1922, 6 pp.

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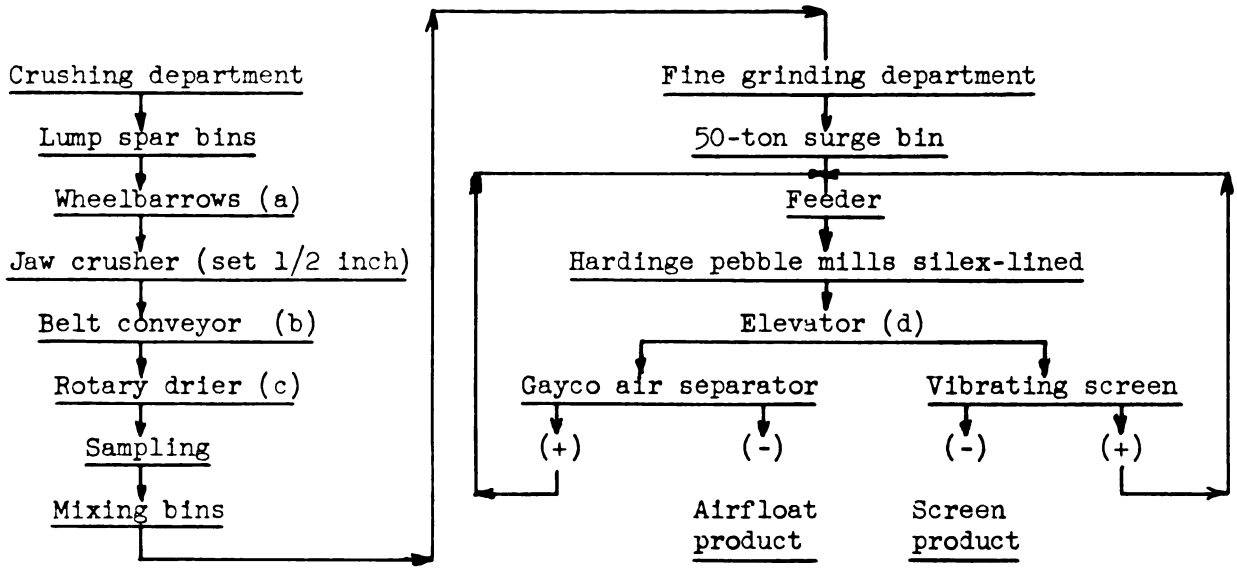

Notes: a. Fines from hand forks screened; plus 1/4-inch run separately, undersize rejected as waste. b. Magnetic head pulley removes 0.2 lb. per ton of tramp iron. c. Ruggles-Coles drier, 70 in. x 30 ft., with silex lining, 5-1/2 r.p.m. Capacity, 8 to 1/2 percent moisture, 10 tons per hour; using 17 lb. coke per ton. A No. 55 Clarage exhaust fan removes mica, clay, and other material minus 40-mesh to 8 ft. cyclone collector (waste). d. Elevator discharges either to air separator or to screen, according to whether the product being prepared is fine (120 to 250 mesh) or coarse (20 mesh). If product of intermediate size (40 to 100 mesh) is being made, the fines are first removed in the Gayco separator and the coarse material, instead of being returned to the Hardinge mill, is transferred to vibrating screen, where final sizing is accomplished. About half the oversize from the Gayco separator may be sent to a tube mill (not shown), which reduces it with less power than the conical mill and increases plant capacity about 8 percent.

Figure 1. - Dry-ground feldspar mill.

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Before undertaking to separate feldspar from quartz and other associated minerals by flotation, it is usually necessary to remove iron-bearing slime by preliminary treatment, which usually takes out the mica as well. As feldspar is so readily altered (kaolinized), it is also necessary to clean up the surface of the particles. Partial kaolinization, even when invisible, may so activate the quartz as to make it float with the feldspar.

Feldspar can be floated with soap, but cationic reagents are commonly employed in pulps acidified with hydrofluoric acid. In the Bureau's laboratories, laurylamine hydrochloride has been the principal reagent, although other long-chain amines may be employed successfully. Considerable secrecy surrounds operations of commercial plants, but it is believed they employ the 800-series reagents of the American Cyanamid Co., whose engineers have assisted in developing the process and tuning up the mills. Some preference has been expressed for pneumatic machines, especially the Steffensen type, rather than mechanically agitated flotation machines for floating feldspar and certain other nonmetallic minerals, although the latter also are employed successfully.

In Europe feldspar continues to be ground occasionally in wet pans, but in the United States and Canada fine grinding is conducted continuously in pebble mills with air separation. However, at one or two small plants dry-batch grinding is still practiced for ceramic and enameler's spar.

MICA

During the Second World War, mica supply was rated at times as being the No. 1 strategic mineral-procurement problem. This mineral is a raw material of first importance in the electronics industries and is useful for numerous other purposes. High-grade sheet mica is deemed essential in the construction of both combat radar equipment and intricate communications equipment necessary for coordinating combatant units on land, sea, and in the air. As the mining and preparation of mica require a large amount of hand labor, the domestic mica industry finds it more and more difficult to compete with low-cost imported material.

Muscovite, or "white mica" ($H_2KAl_3(SiO_4)_3$), and phlogopite, or "amber mica" ($(H,K,Mg,F)Mg_3Al(SiO_4)_3$), are the micas of commerce. Biotite and other varieties of "black mica" are virtually unsalable; (except, perhaps, as ground mica) lithium and vanadium micas, however, are valuable as ores of the respective metals. Phlogopite occurs in basic pegmatites. It is used almost exclusively in the form of splittings and has been mined principally in Canada and Madagascar and to a minor extent in Mexico. As no phlogopite deposits of commercial grade are known in the United States, the remainder of this section will be devoted entirely to muscovite.

The useful micas are readily distinguished from other platy minerals by the flexibility of the thin sheets, which can often be wrapped around a pencil without cracking. Muscovite occurs in granite pegmatites, usually in flat, six-sided crystals or "books," which can be split easily and accurately into transparent films whose thinness is limited only by the dexterity of the operator. The perfect basal cleavage is determined by the

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layer lattice, which, of course, has the thickness of a single molecule. These films are highly resistant to fire, water, acid, or electricity, and their properties remain virtually constant under high heat or extreme cold.

Most of the mica books found in pegmatites and all mica from schists and other deposits are valuable only as grinding scrap, and the value of the remaining high-value portions varies greatly, depending chiefly on the size and quality of flat sheets into which it can be split. "Strategic mica", including all sizes and qualities of mica used in the manufacture of equipment for the armed forces, has been defined as block or punch mica in the rifted (roughly split and trimmed) condition that is of quality better than stained, (i.e. "good-stained or better"), free of cracks, pinholes, cross grains or reeves (breaks or tears in splitting), and ribs (waves or ridges), and relatively free of clay staining.

Muscovite films or thin sheets may be greenish, brown, or reddish. Some of the best qualities have a clear ruby color. Spotted or stained mica, which contains thin scales or streaks of iron oxides or other minerals, is worth less than clear, transparent mica, even though its usefulness may not be greatly impaired. Clay staining may be tolerated if slight but may ruin the material for any purpose. Strategic sheet mica must be free from crystallization flaws, mechanical defects, or inclusions of other minerals. Tangle'sheet, "herringbone", or "A" mica split imperfectly. Ruled mica splits into ribbons across the cleavage planes, and wedge mica splits into films that are thicker at one end than at the other. If inclusions are present, the mica may be described as (1) heavy-stained, (2) red-stained, (3) clay-stained, (4) light-dotted-stained, (5) black-dotted-stained, (6) black-stained. Color alone is no sure sign of quality. Clear ruby-colored mica, however, almost always possesses a sufficiently low power factor and other properties for satisfactory use in condensers, whereas the power factor of clear mica of greenish or other dark hues varies from deposit to deposit.

The smallest circular size, designated as "small punch," yields disks at least 1 inch in diameter. "Punch mica," the next larger size, must be large enough to yield a circular disk 1-1/2 inches in diameter. "Circle" mica yields disks 2 inches or more in diameter. "Sheet" mica includes material larger than about 1-1/2 by 2 inches that yields rectangels (or equivalent areas with a minimum width of 1 inch). However, the minimum size of ordinary electrical-quality sheet is 2 by 2 inches.

Uses. - Strategic block or sheet mica is employed in condensers or capacitors for radio, radar, telephone and miscellaneous communications, depth sounding and submarine detection equipment, and in magnetos for airplanes and other military conveyances. It is also employed in radio tubes for bridges and spacers, airplane spark plugs, gage glasses, compass cards, diaphragms, television sets and miscellaneous items. Large quantities of lower qualities of sheet are used as insulation in electrical appliances such as flat irons and toasters.

Mica splittings are used in the manufacture of built-up mica plate, which has numerous important military and civilian uses, including commutator segments and V rings for motors and generators of all kinds and miscellaneous electrical insulation. The splittings are cemented together with shellac or synthetic resins. They are quite thin, and unless suitable

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mechanical splitting methods can be perfected they are produced almost exclusively in cheap-labor countries. Muscovite splittings are imported principally from India; domestic production is virtually nil. The manufacture of phlogopite splittings is less laborious and sometimes is accomplished mechanically.

Trimmings from books rifted to produce salable block mica as well as those from which no salable block can be recovered are marketable as "scrap mica." This material is converted into ground mica in three principal types of mills, producing, respectively, (1) wet ground, (2) ordinary dry ground, and (3) micronized mica. The output of ground mica includes not only the product made from mica mine scrap but also that from factory scrap, byproduct flake mica from clay washing, and kyanite milling and schist mica. The principal use of ground mica is in roll roofing, although substantial tonnages are also consumed in making wall paper, paint, and rubber goods. Miscellaneous uses include surfacing asphalt shingles, Christmas tree snow, lubricants, annealing, foundry facings, and oil-well drilling mud.

Occurrence and yield. - Muscovite is of widespread occurrence in granites and schists but only in small plates. Certain schists are composed principally of mica. They are increasingly used in the production of ground mica (usually of poorer quality), and byproduct mica from the milling of several kinds of nonmetallic minerals also promises to become more and more important. Granite pegmatites, however, are the only sources of muscovite punch or sheet mica.

In common with all pegmatites, mica deposits are irregular in shape, size, and mica content. Both the quality and quantity vary greatly over wide ranges. The total yield of mica at commercial mica mines ordinarily ranges from 2 to 7 percent, based on rock broken. The actual percentage in the entire deposit is generally even less.

In well-zoned pegmatites having considerable width, it is usually unnecessary to mine the whole pegmatite body. Occasionally other portions can be mined for feldspar, but in such portions the yield of mica is likely to be quite small and the quality poor. In even the best mines, most of the mica is recoverable only as scrap. On the average, only about 3 to 8 percent of mine-run mica is finally obtained in the form of full-trimmed block mica and the yield of high-quality or strategic mica, based on wartime experience, is often only 1 pound per ton of rock. It rarely amounts to as much as 11 pounds. In New England, the average yield[12/] per ton of rock mined at 45 mines in 1943-44 was 1.21 pounds of "equivalent sheet" (pounds of sheet plus 1/10 the weight of punch), and for the 10 best mines it was only 3.3 pounds.

Production and trade. - The United States has recently produced about 70 percent of all the mica sold or used in the world, but this large tonnage of domestic mica consists mainly of scrap, byproduct mica, and ground mica from schist. India, in addition to producing most of the world's splittings, has been the source of over two-thirds of the sheet-mica supply, although increasing quantities have been coming from South America and presumably also from the U.S.S.R.

12/ Bannerman, H. M., and Cameron, E. N., loc. cit.

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The domestic production of unmanufactured sheet mica (excluding scrap) averaged 1,140,724 pounds per year, valued at $185,714 during the prewar period 1935-39 and rose to an all-time peak of 3,448,199 pounds, worth $3,228,742 in 1943. By 1948 it had dropped to 270,042 pounds with a value of only $45,940. The wartime figures, it should be noted are in no way comparable with those for earlier years. In 1943, for example, the output was predominantly full-trimmed mica prepared in accordance with the educational work and the subsidy buying program of the Colonial Mica Corp., which was the Government's buying agency. After the war, many mines went out of business, and others reverted to the former practice of marketing "thumb-trimmed" or half-trimmed mica for civilian uses.

Imports of uncut sheet and scrap are likewise not comparable with domestic production statistics, as foreign mica is more closely trimmed, especially that from India. They reached a wartime peak of 5,501,745 pounds valued at $6,313,900 in 1943 and declined to 1,754,419 pounds worth $1,150,958 in 1945. The prewar average (1935-39) was only 750,674 pounds with a value of $222,549.

On the basis of the foregoing figures, domestic consumption of punch and sheet, despite the poor showing of domestic mines, was substantially larger in 1947 than it was before the war. Although the proportion of lower grades was larger after the war than it was during the period when home appliances were not manufactured, the demand for higher-quality mica is undoubtedly much greater today than it was before Pearl Harbor, partly by reason of the largely increased use of electrical devices. On the other hand, foreign mica-processing industries have been established in producing countries where labor is cheap. This practice tends to lower the imports of crude block or sheet and to increase imports of material cut or stamped to size.

The consumption of splittings also has increased. The prewar average was only 3,097,865 pounds a year. After rising to 8,816,965 pounds in 1944, it declined and then rose again to an all-time high of 9,309,981 pounds in 1947.

The increase in consumption of scrap mica and ground mica is spectacular. Until the mid-1930's, it only occasionally amounted to as much as 10,000 tons a year. By 1937 it had jumped above 30,000 tons, and during the war it rose to over 50,000 tons. After falling off a little in 1945, it headed upward again. Imports also have been rising, with the result that in 1946 sales of ground mica soared to 62,113 tons valued at $2,516,018. Beginning in 1947, a supply of byproduct mica was augmented by initial production at feldspar flotation mills.

Although at least 25 States have contributed more or less to the total, the actual production of domestic mica has come principally from North Carolina, New Hampshire, Connecticut, South Dakota, Georgia, and New Mexico. Minor sources during the recent war were Alabama, Arizona, California, Colorado, Idaho, Maine, Massachussetts, Nevada, Pennsylvania, South Carolina, and Wyoming. In all but a few years, North Carolina has been by far the leading producing State.

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India has remained the world's most important mica-producing country because of its relatively numerous and high-grade deposits and abundant cheap labor. Production in Latin America, especially in Brazil and Argentina, has increased significantly in recent years. Wartime conditions also expanded production in a dozen or more other countries, but not enough, tonnagewise, to foreshadow substantial change in the international supply picture. Apart from India and Latin America, Canada, Madagascar, Southern Rhodesia, and British South Africa are the only countries that have made any but rather small token shipments to the United States.

Prices. - The price as well as total sales of scrap mica have risen sharply. This is the most important mica product from the standpoint of miners of other pegmatite minerals to whom mica is a byproduct. According to location and quality of the mica, the range was from $6 to $20 a ton, averaging $13, during the 1935-1939 period. In 1947, the spread in Western States was from $17.50 to $20 per ton, and in the East from $18 to $35. Prices of imported scrap, as reported by mica grinders, ranged from $24.50 to $40 per ton at plants. As calculated from import statistics, the average for foreign scrap was only a little over $12, compared with less than $7 in 1939, but these figures are foreign valuations that exclude freight and other charges.

In 1946 the average price of all domestic sales of ground mica was a little over $40 a short ton. This figure would be higher, were it not for the fact that it includes mica recovered from kaolin and schists and valued at an average of only $19 a ton. In December 1948 the prices quoted by the Oil, Paint, and Drug Reporter ranged from 3-3/8 to 3-5/8 cents per pound for dry-ground mica, f.o.b. plant, and from 6-3/4 to 7-3/4 cents per pound for wet-ground in bags (freight allowed). These figures are substantially higher than quotations for earlier years. According to the E & M J Metal and Mineral Markets, prices f.o.b. North Carolina mills remained at $50 to $80 a short ton for dry-ground and $135 to $175 per ton for wet-ground mica.

Prices for domestic sheet and punch mica are once more based on negotiation between buyer and seller. During the war, the Government bought virtually all grades of mica at a flat price. The only distinction under the wartime contracts was that small sizes had to be full-trimmed, whereas sizes larger than about 1-1/2 by 2 inches were only three-fourths trimmed. In 1939, punch mica from domestic mines sold at around 5 cents a pound and larger sizes at increasing prices up to about $10 for good clear sheets 8 by 10 inches. The average reported for the entire domestic output in that year was 17 cents a pound. Under the government's one price plan, designed to increase recovery of small sizes that formerly had gone mostly into scrap, the price was established at $5 in 1943 and later advanced by stepwise bonuses. As much of the domestic product failed to meet the requirements for suitably trimmed and qualified mica, the average price of all domestic sales was lower, but in 1944 it reached a record of $2.14 a pound; in 1947 it was down to 28 cents, owing not only to the withdrawal of subsidies but also to the discontinuance of closer trimming.

Indian Bengal mica has been marketed under a system that recognizes 9 standard qualities (classes) and 14 sizes (grades), a total of 126 categories. As most imported muscovite sheet undergoes at least three separate

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handlings for trimming, grading, and qualifying, requiring an astonishing amount of time and labor simply to prepare it for market, its prices are not at all comparable to domestic mine products. The latter contain more waste and are less carefully selected; hence, they fetch lower prices per pound even when the inherent quality of the mica is equally good.

Following is a comparison of the values of domestic uncut sheet mica in 1939 and 1946, as calculated from reports to the Bureau of Mines:

Average sales values of domestic uncut sheet mica per pound

Size, inches	Clear		Stained or spotted	
	1939	1946	1939	1946
Punch	$0.056	$0.13	$0.055	$0.14
1-1/2 x 2	.299	.96	.184	.54
2 x 2	.515	1.47	.267	.86
2 x 3	.778	2.00	.479	1.68
3 x 3	1.104	2.61	.653	1.90
3 x 4	1.372	3.00	.824	2.80
3 x 5	1.767	3.71	1.043	3.01
4 x 6	2.812	4.48	1.284	4.03
6 x 8	4.167	5.67	1.398	5.08
8 x 10	7.935	8.15	2,071	-

Mining and treatment. - Mica mines are typically small and usually shallow. Common practice in this country has been to mine rich pockets or zones, largely by hand, and to abandon a deposit as soon as it becomes unprofitable. During the war, Government assistance was given to operators, including the rental, at nominal fees, of portable compressors, jack hammers, pumps, and hoists but the amount of mechanization possible is usually limited by the size of the deposits. In Brazil, mines have been opened in a large, deeply weathered pegmatite, or following a series of closely spaced smaller deposits, using a bulldozer. This method is cheap and effective, particularly when the topography allows gravity disposal of the material removed, in which case books can be picked up by unskilled workers who follow the bulldozer or comb the dump. It is not applicable, however, to many deposits and at hard-rock mines can be used only to clear out old workings or to turn over dump material, occasionally also in stripping.

At sheet-mica mines, the prices paid for properly prepared products are much higher than those for run-of mine mica, partly because quality can be appraised more readily. On the other hand, inexperienced workers can spoil much good mica by improper trimming and rifting. Until instructed by the Colonial Mica Corp. during the war, most mica miners sold their entire "mine-run" output to a trimming shed or traveling buyer. Some sold roughly graded sheet, but only a few actually prepared the mica for use in manufacturing establishments. Contract sales direct to manufacturers were almost always small and consisted mainly of stove and lamp-chimney grades.

The steps of preparation of sheet mica include (1) cobbing or sorting, (2) rifting or sheeting, (3) trimming, (4) grading (sizing), (5) qualifying.

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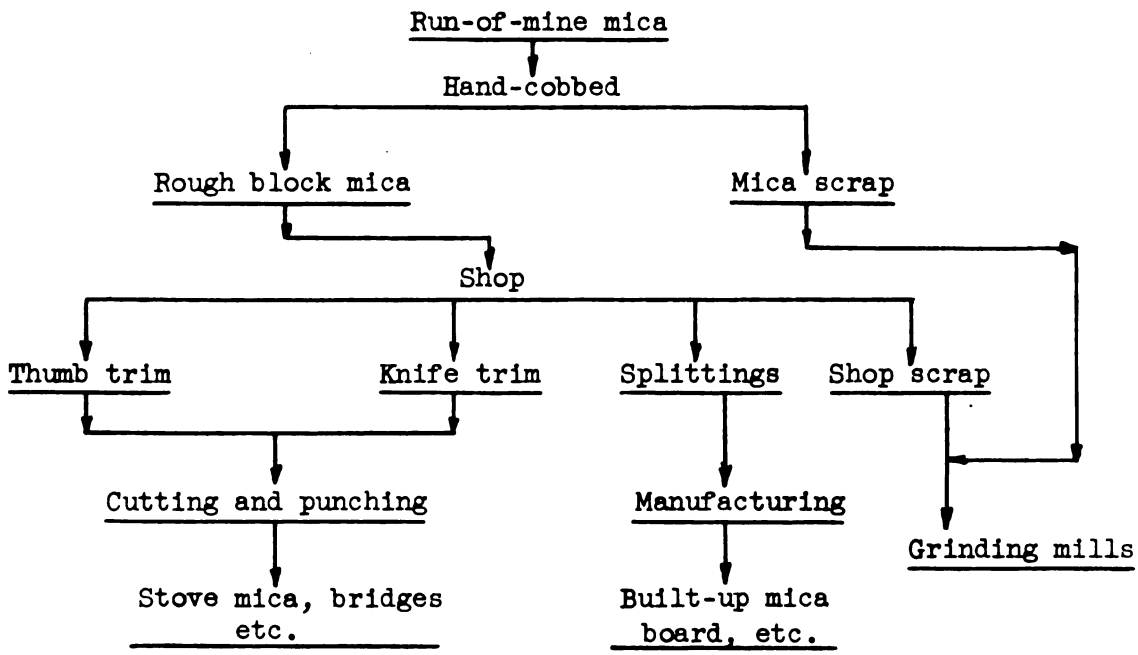

Figure 2. - Preparation of sheet mica.

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After the books are picked out of the muck after a blast, they are usually all taken to a shed or open space and cobbed to remove dirt and rock from the crystals and to sort out those that are valuable only as scrap. Rifting is the operation of splitting the cobbed mica into sheets or plates, usually less than 1/16 inch thick. A special type of knife is used. The products are (1) untrimmed block or mixed sizes, (2) punch and washer stock, and (3) scrap.

Domestic mica is usually thumb-trimmed. Ragged edges are broken from the rifted block with the fingers; if a knife is used, only a minimum of usable mica is removed. Knife-trimmed block is closer trimmed than thumb-trimmed mica. Full trim is trimmed on all sides, three-fourths trim on three sides and half trim on two adjacent sides.

Grading is done in accordance with a suitable grading chart or templet, which may vary somewhat according to the market. Typical charts together with additional information on the preparation of strategic mica are presented in Bureau of Mines Information Circular 7258 by G. Richards Gwinn and Information Circular 6822 by F. W. Horton.

Many trimming shops engage in the manufacture of cut-mica products of various kinds. A flow sheet of an integrated operation is shown in figure 2.

Wet grinding of mica is accomplished in home-made chaser mills with large wooden wheels and a bottom die ring formed of hardwood blocks set end grain up. As even the thinnest mica flakes are tough, elastic, and too slippery to be grasped or torn by ordinary machines, the main action is delamination. Wet-ground mica is worth more than dry-ground, principally because of its appearance, so every effort is made to preserve the sheen. Dry-ground mica looks in contrast very much like flour, as the edges of the mica flakes are torn and hackly, and even the faces may be abraded. Hammer mills are commonly used for dry grinding, followed by screens. Additional details regarding various types of grinding mills will be found in an earlier paper.13/ Micronized mica is produced in jet impact machines.

At byproduct plants, mica is usually partly eliminated by screening, as the mica flakes resist comminution. In deeply weathered outcrops, clay may be washed out; in some cases even the mining is done hydraulically. Mica is then recovered partly by hand picking and partly by alternate screening and crushing.

Combinations of round- or square-holed screens with elongated openings may produce selective separation of other minerals of similar mesh size but blocky rather than tabular or flaky. Wet shaking tables and occasionally jigs have been employed to separate sand. Air-table separation of dry material is fully as effective and is claimed to remove partly delaminated material that can be reground. This is a decided advantage in respect to roofing mica or wherever bulk density or maximum surface covering power is important.

Ordinarily the most economical method of reclaiming finely divided mica (under about 20 mesh) from mixed mineral suspensions is froth flotation.

13/ Tyler, Paul M., Technology and Economics of Ground Mica: Trans., A.I.M.E., vol. 148, 1942, pp. 105-121.

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Although mica can be floated by anionic reagents, cationic collectors are superior. The affinity of long-chain amine reagents (e.g., laurylamine hydrochloride) for the platy mineral is enhanced by acidifying the pulp, and the separation from granular silicates is made more selective by additions of aluminum salts, either aluminum sulfate or potassium alum. A starvation diet of the filming reagent is recommended, as too much of it makes the separation from other silicates less selective.

QUARTZ

In many pegmatites, the crystalline quartz is relatively free of inclusions of other minerals and so may be suitable for use as potter's flint and for other uses requiring material that is quite low in iron. Almost never can it be employed for radio or even optical fusing crystals. At a time when Danish or Belgian flint pebbles were hard to get, some feldspar grinders used handcobbed quartz from local mines as a grinding medium, but only as an emergency substitute. Pegmatite quartz has been favorably received in the manufacture of crushed grains for coated abrasives, bitstone, or placing sand at potteries, and for special refractory uses, but the quantities used for such purposes are rather small. Of more practical importance is the use for high-grade glass batches instead of ordinary glass sand in localities where the delivered cost of natural sand of suitable quality is relatively high. The principal uses of crude or roughly crushed quartz are for metallurgical flux, for making ferrosilicon, for filling acid towers, and for grinding to silica flour.

The total marketed production of crude, crushed, and ground quartz in the United States from pegmatites, veins, or quartzite rose in 1943 to 99,445 short tons valued at $346,558, the largest tonnage since 1917, when 142,673 tons was reported. Much of this quartz was used in newly built wartime ferrosilicon plants in the Pacific Coast States. In 1947 the quantity was only 73,347 tons, but the value was $368,977, an all-time record. Of this total, 21,940 tons was sold crude at an average value of $5.39 a short ton, f.o.b. mines; 34,199 tons was sold crushed at an average price of $3.95; and 17,208 tons was marketed ground at an average of $7.90. To avoid duplication, the ground material herein reported is only that ground by the original producers of the crude quartz or those who purchase from farmers or small miners not reporting to the Bureau of Mines. Both crude and crushed quartz are bought by various mills that grind silica flour for ceramic uses, paints, fillers, etc. Such material competes with powdered silica produced by grinding sand and sandstone. Sales of the latter amounted in 1942 to 651,120 tons worth $5,181,113, or $7.96 a ton.

The average value figures for crude and ground quartz in 1947 are historically abnormal. In 1945, for example, the former brought an average price of $2.96 a ton, whereas ground material was worth $15.25 a ton. The quantity of ground quartz reported in 1947 was over four times the 1945 figure, and in 1942, another big year, when sales rose to 18,088 tons, the average value also was under $10 a ton. Artificial glass sand, produced as a byproduct of feldspar milling and valued at $5 to $10 a ton, may be reported under the classification of either "crushed" or "ground" and so may account for this wide fluctuation in average values.

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Quotations in December 1948 on ground "hard quartz" silica (99-1/2 percent grade, car lots, in bags), according to the Oil, Paint and Drug Reporter, were $15 a ton for 325-mesh and $10 a ton for 140-mesh.

BERYL

Beryllium, or glucinum, as it is called in England (element No. 4) is a very light metal. It has about the same density as magnesium. Although it possesses other characteristically desirable properties as an engineering metal, notably high rigidity, its principal metallurgical employment seems destined to be as a hardening agent for other metals. The outstanding use has remained in copper beryllium alloys, which find an increasing range of applications. Other beryllium alloys are of minor importance. Small quantities of the pure metal are used for windows for X-ray tubes because "soft" (long wave-length) radiation will pass through. Beryllium was suggested for use as a moderator in the piles and for other uses at atomic-energy plants, but other elements have been substituted wherever possible owing to the difficulty of obtaining adequate supplies. Beryllium oxide or zinc beryllium silicate is employed rather intensively as a phosphor to develop yellow-white light in fluorescent lamps. Beryllium oxide is also used in growing amounts for super-refractory crucibles and shapes.

Beryl ($Be_3Al_2(SiO_3)_6$) has remained virtually the only commercial ore of beryllium. Owing to the importance of the uses of the metal and its salts, beryl is a strategic material. As the flow of supplies is irregular and somewhat unpredictable, it is one of the minerals purchased for Government stock-piling. This mineral contains only 5 percent of the metal when pure, and it is seldom found pure. Beryl crystals are notoriously subject to partial replacement even though they may retain their characteristic structure and general appearance.

Phenacite (Be_2SiO_4) is much richer than beryllium and so is chrysoberyl ($BeAl_2O_4$). These minerals are occasionally associated with beryl in pegmatites but are even scarcer and hence have not proved commercially important.

Occurrence. - Although, as later noted under the section on gems, a few emerald deposits are found in other formations, all commercial deposits of industrial beryl have been in pegmatites. In well-oriented deposits, it is frequently encountered in the contact and wall zones, but single large crystals or nests of crystals occasionally occur in the interior zones.

It is believed that beryl may be formed at three different stages. The earliest-formed beryl occurs in zones as small anhedral crystals, skeletal crystals or "shells," and corroded anhedral grains associated with plagioclase, mica, and quartz; crystals and anhedral grains of beryl introduced into wall rock are probably of this age, also. Second-generation beryl is observed in zones parallel to the outer edges of very coarse-grained pegmatite cores as very large anhedral or corroded crystals associated with albite, potash spars, quartz, muscovite and lithium and/or tantalum minerals. Third-generation beryl is represented by gem material that is likely to develop in small quantities lining vugs, and hence is one of the last pegmatite minerals to form.

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Crystals and fragments large enough to be recoverable by hand-sorting are principally of the second generation. Individual crystals sometimes weigh several tons. However, much of the beryl of this intermediate stage of pegmatite development is too small (usually under 1 inch in diameter) to recover except by milling, and virtually none of the first-generation beryl is released until the rock is crushed.

The beryl content of most pegmatites is quite small, seldom exceeding 1 percent. The famous Las Tapias mine in Argentina, now exhausted, is probably the only one that produced beryl as its main product. Most of the Brazilian output is a joint product of tantalum-columbium ores, whereas the Indian output has come mainly from mica mine dumps. Domestic production has come principally from South Dakota lithium-bearing deposits and to a less extent from feldspar and mica mines in other States.

Production. - World production of beryl amounted to less than 500 tons a year prior to about 1937 but increased rapidly as a result of the purchasing programs of the United States Government during the war. In 1941 it totaled 4,090 metric tons and, after a slight decline in 1942, attained an all-time record of 5,101 metric tons in 1943.

Before the war, most of the world's supply came from Argentina and Brazil, but production in Argentina declined sharply after 1941. Brazil has recently become the principal producing country, although India has also been an important source for several years. Domestic production has generally been less than 100 tons a year but rose to 269 short tons in 1942 and reached a peak of 388 tons in 1944.

Markets and prices. - For many years beryl was quoted at $30 a short ton for material containing 10 percent BeO and $35 a ton for the 12-percent grade. To stimulate production for war uses, prices advanced after about 1940, rising to $75 to $100 a ton in 1942 for 10- to 12-percent material. In May 1944 the Metals Reserve Co. boosted the price to $14.50 per short-ton unit, basis 8 to 12 percent BeO, equivalent to $145 a ton for 10-percent grade.

Beryllium ores, metals, and salts were under strict wartime control until early 1945, although government purchasing was discontinued at the end of 1944. As the last of these controls was lifted, near mid-year 1945, quoted prices dropped to $9 to $12 per unit, but later they rose far above the wartime level. Late in 1948 the quotation was $24 to $26 a unit for 10 to 12 percent grade, f.o.b. domestic mines. This price is nearly as high per unit as the prewar price per ton.

Mining and treatment. - Commercial recoveries of beryl have been wholly the result of hand selection. Under present conditions, this is probably the most economical method of recovering fragments over about 1 inch in diameter, but mechanical methods are necessary for small grains, except perhaps in cheap-labor countries, where the minimum size for economical hand picking may be half an inch or less. The specific gravity of beryl (2.65 to 2.84) is normally a trifle higher than that of feldspar or quartz but enough to favor gravity methods of separation, particularly in view of the fact that the mineral is so often subject to partial replacement by

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lighter minerals. As liberation is generally complete at sizes well above 10 mesh, processes that would treat coarse sands are desirable according to the millman's precept "to recover the mineral when free," and also because the optimum size for crushing associated minerals, quartz and feldspar, for use in the glass industry is about 14 mesh. On the other hand, froth flotation at present appears to be the most economical method of recovery, and this method does not usually treat even nonmetallic minerals much coarser than 35 mesh.

Beryl is a "soap floating" mineral, but acids or saponified fatty-acid reagents are rather nonselective as between beryl, feldspar, and mica. Some ores can be floated in the natural state, but others require drastic treatment to obtain a clean surface on the mineral. Thorough scrubbing with alkali and washing to remove surface alteration products is a successful preliminary treatment for some ores, but cleaning with hydrofluoric acid often proves more effective. Suitable reagent combinations and procedures are described in several Bureau papers.14/

LITHIUM MINERALS

Commercial sources of lithium and its salts include spodumene ($LiAlSi_2O_6$), amblygonite ($LiAlFPO_4$), lepidolite ($LiKAl_2F_2Si_3O_9$), and occasional small quantities of several other typical constituents of granite pegmatites. Recently, however, byproduct dilithium sodium phosphate, recovered as a flotation concentrate from potash-bearing salines at Searles Lake, Calif., has become the major source.

Before the recent war (1935-39), the annual shipments of lithium ores and compounds from domestic mines averaged 1,327 tons worth $48,280 and containing 88 short tons of Li_2O. New mines and plants were opened during the war to supply lithium compounds for highly specialized uses, notably the employment of lithium hydride as a lightweight carrier of hydrogen for inflating radio-antenna balloons included in Navy rescue equipment. In 1944, shipments from domestic mines rose to a record total of 13,319 tons of ores and compounds valued at $552,977 and representing 848 tons of Li_2O. Collapse of Government orders ushered in a difficult reconversion period during which byproduct production increased, and the principal pegmatite-mining operations at which lithium ores were the main product had to close. In 1947, the Li_2O content of shipments from domestic mines, including some byproduct minerals from South Dakota and Colorado pegmatites but mostly from Searles Lake, was 199 tons. Whereas this quantity was less than one-fifth of the wartime peak demand, it was more than twice the prewar needs, and in 1948 the production of spodumene was greatly expanded. Additional quantities of lithium are imported from Southwest Africa, chiefly in the form of lepidolite for use in the glass industry.

14/ Lamb, Frank D., Beneficiation of New England Beryllium Ores; Bureau of Mines Rept. of Investigations 4040, 1947, 9 pp. Snedden, H. D. and Gibbs, H. L., Beneficiation of Western Beryl Ores; Bureau of Mines Rept. of Investigations 4071, 1947, 18 pp. Kennedy, J. S. and O'Meara, R. G., Flotation of Beryllium Ores; Bureau of Mines Report of Investigations 4166, 1948, 18 pp.

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Civilian demands for lithium compounds, although still small, are increasing. Lepidolite and, to a less extent, spodumene and, perhaps, amblygonite are used as fluxes to improve the properties of special kinds of glass and in ceramic glazes, enamels, and porcelains. They are also employed as opacifiers. Natural or artificial mixtures of spodumene and microcline have been employed partly to replace feldspar in whiteware bodies, lowering the fusion temperature several cones and thereby conserving time and fuel.

The use of lithium chloride and bromide for air conditioning has fallen short of expectations but may still grow to substantial proportions. More and more lithium compounds are used in ceramics and glass and in lubricants. Lithium oleate is used for airplane greasing because of its resistance to wide temperature changes, and similar lithium soaps may find employment as industrial detergents or cleansers under special conditions. Lithium compounds are used in the Edison-type storage battery. Lithium carbonate and lithium-strontium-nitrate are used in pyrotechnics to produce red flames. For many years, the principal use of lithium salts was for fortifying mineral waters, but medicinal uses have become relatively small in comparison to potential industrial uses of the metal and its compounds.

Lithium is the lightest solid element (sp. gr. 0.543). It weighs only 34 pounds per cubic foot compared, with 169 pounds for aluminum and 710 pounds for lead. It is malleable and ductile enough to be rolled into thin plates or drawn into wire. It melts at 180° C. and boils at 1,400° C. Although it resists atmospheric attack better than its sister alkali metals, sodium and potassium, it is far too active chemically and far too soft to be used unalloyed as an engineering metal. Its principal metallurgical uses have been as a scavenger and grain-refining alloy and as a flux for other metals. It is not merely a deoxidizer. It also has a high affinity for nitrogen, hydrogen, sulfur, phosphorous, carbon, and silicon, and the resulting nonmetallic compounds are so fluid and light that they are readily removed in the slag or evolved as gases at pouring temperatures. Lithium chloride and fluoride are used as a flux in welding aluminum. It is also a hardening agent for lead. It finds employment as a "getter" to remove traces of gases from vacuum tubes and has been recommended for atmosphere control in metallurgical furnaces to prevent oxidation.

Pound for pound, lithium is the most efficient metallic reducing agent; its atomic weight (6.95) is below that of any other element except hydrogen and helium, both gases. One of the three isotopes of lithiun is radioactive. Lithium fission has been considered as a source of atomic power. Although the uranium atom releases more than 10 times as much energy, it is 33.5 times as large. On an equal mass basis, therefore, lithium is theoretically three times as efficient, far more abundant in nature, and vastly easier to isolate in the elemental state. On the other hand, no one seems yet to have developed a chain reaction that will keep the atom-splitting process going. In fact, it is not at all certain that this can be done.

Occurrence. - Known reserves of lithium ores are ample to supply greatly increased demands. Additional quantities are available from pegmatites in various parts of the world. Lithium is also present as a minor constituent of saline deposits and is likewise found in several micas and other minerals in amounts ranging from a mere trace to 1 percent or more. If need arose, some of these substandard sources could be drawn upon.

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However, the resources that can probably be made to supply largely increased tonnages most promptly are the spodumene deposits in South Dakota and North Carolina, where measured reserves of this mineral are of the order of many thousands of tons, and inferred reserves are in millions of tons. Amblygonite, being somewhat richer than spodumene, has been a preferred source but is more erratic in occurrence and probably scarcer. Lepidolite is one of the most widespread lithium minerals, but most deposits are rather small. Notwithstanding its low lithium content, it is a valued ore, being often used in the natural state and also as a raw material for the extraction of rubidium and caesium as well as lithium.

As lithium mineralization is a relatively late phase in the formation of complex pegmatites, most pegmatites contain little or no lithium minerals. Of the few that do carry lithium minerals, many do not carry them in any considerable quantity. On the other hand, the lithium content of pegmatites in North Carolina and possibly in one or more other areas is remarkably uniform. Such pegmatites are usually tin-bearing and may contain columbo-tantalite, although not necessarily in sufficient quantities to be recovered readily. Unlike most pegmatites, those that are richest in lithium minerals are likely to be relatively poor in feldspar. However, in South Dakota a typical occurrence is in the form of interior zones of spodumene-quartz-albite surrounded by quartz-albite-muscovite pegmatite.

For further discussion of the geology of lithium deposits, reference may be made to other Bureau of Mines publications.

Prices. - Trade-journal quotations for lithium ores were advanced over wartime prices in 1947. As reported in E & M J Mining and Minerals Markets for December 1948, they were as follows: spodumene, 6 percent grade, $6 to $8 per unit of 20 pounds of contained Li 0, carlots; amblygonite, 8 to 9 percent Li_2O, $110 per short ton, f.o.b. mine; lepidolite, 4 percent Li_2O, $80 per short ton, f.o.b. mine. These prices are substantially higher than those quoted in 1946. Li_2O contents of dilithium sodium phosphate have been valued at around $9 a unit. Lithium metal is quite expensive owing to the cost of isolating it from its compounds. On government orders it cost $12.50 a pound, and smaller commercial quantities sold before the war at $15 to $20 a pound based on large-scale operations. However, a $5 price appears to be a reasonable long range possibility.

Mining and treatment. - At several mines in South Dakota and elsewhere, lithium minerals are present mainly in the form of crystals large enough to be recovered easily by hand cobbing and sorting. Better recoveries of lithium as well as of associated minerals are indicated by the recent adoption of heavy-media (sink-float) separation. Jigs and tables have been employed in this area, notably by the Black Hills Tin Co. near Keystone, S. Dak., but in 1948 the Lithium Corporation of America was recovering spodumene from the Edison mine by sink-float and the Dutch mines cyclone.

15/ Hess, Frank L., Lithium: Bureau of Mines Inf. Circ. 7054R, 1943, 14 pp. Clarke, Fremont, F., Zinner, Paul, and Others. Edison Spodumene Mine, Pennington County, S. Dak.: Bureau of Mines Rept. of Investigations 4234.

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The large and remarkably uniform pegmatites in the vicinity of Kings Mountain, N. C., contain an average of over 20 percent spodumene in the rock as mined but do not yield much marketable mineral by hand sorting. For deposits of this type, froth flotation appears to be the most economical method of treatment. According to Norman and Giesecke,16/ highly selective flotation of spodumene can be obtained with almost any anionic collector. Oleic acid, soaps, and fatty acids generally gave good results in neutral or acid pulps. Sulfated, sulfonated, and phosphated fatty compounds gave excellent separations in an acid pulp. The main problem with most ores was preparation of the mineral surfaces before filming. Drastic scrubbing or attrition treatment with cleaning reagents was usually necessary; sodium hydroxide alone or with sodium sulfide was a suitable detergent.

By adding a small amount of cationic collector (long-chain amine), mica can be thrown into the spodumene concentrate or it can be recovered subsequently from the quartz feldspar tailing. If feldspar does not have to be separated, feldspar and spodumene can be floated together, using the same reagents as for feldspar alone, namely, a long-chained amine in the presence of fluorine. Beryl, if present, tends to float with spodumene. Although this can probably be prevented by employing suitable depressants, mixed concentrates can usually be separated by gravity.

A method of concentrating spodumene by decrepitation followed by screening was devised in the Bureau of Mines laboratories.17/

Methods for breaking down various ores and recovering lithium therefrom are described in other Bureau publications. One method is chloride volatilization18/ and another involves calcination with gypsum followed by a hot-water leach.19/

COLUMBIUM-TANTALUM MINERALS

Tantalite and columbite form an isomorphous series. Specimens from all localities generally contain both tantalum and columbium, and the name of the mineral depends on which element is present in larger proportion. For economical employment in industry, however, tantalite should contain not less than 30 percent and preferably 45 percent Ta_2O_5, and the total Ta_2O_5 plus Cb_2O_5 content should not be less than 60 percent. Columbite should contain a minimum of 45 percent Cb_2O_5, and the Ta_2O_5 is preferably low; some contracts specify a 10:1 ratio.

Microlite is another pegmatite mineral that is classed as an ore of tantalum; it is a calcium tantalite.

16/ Norman, J., and Giesecke, E. W., Beneficiation of Spodumene Rock by Froth Flotation: A.I.M.E. Publication 1161, 1940.

17/ Fraas, Foster, and Ralston, Oliver C., Beneficiation of Spodumene by Decrepitation: Bur. Mines Report of Investigations 3336, 1937, 13 pp.

18/ Fraas, Foster, and Ralston, Oliver C., Chloride Volatilization of Lithium from Spodumene: Bur. Mines Report of Investigation 3344, 1937, 11 pp.

19/ Cunningham, J. B., and Gorski, C. H., Recovery of Lithium from Its Various Ores and Salts: Bur. Mines Report of Investigation 4321, 1948, 35 pp.

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Uses. - Columbium, in the form of its ferroalloy, is added to stainless steels in quantities of 0.5 to 0.8 percent to improve weldability, creep strength, and impact resistance. The element is also used in various high-heat-resisting alloys for jet propulsion and gas turbines and has sundry minor uses.

Tantalum is used principally as a getter in radio and radar tubes; as a catalyst in the manufacture of synthetic rubber, and in hard-carbide cutting tools. Minor uses are for corrosion-resistant linings and parts of chemical equipment, in surgery for skull plates and sutures, and for special camera lenses.

Occurrence. - Tantalum and columbium minerals are found only in pegmatites or in eluvial and alluvial concentrations from eroded pegmatites. They are quite rare. Few pegmatites contain them at all, and still fewer carry them in quantities sufficient to be recoverable. When present, they are likely to accompany tin and other heavy minerals in interior zones. These zones are likely to be rich in spodumene or beryl or both.

Production and trade. - Domestic production has been small. The wartime peak in 1943 was only 5,777 pounds of columbium concentrates and 9,411 pounds of tantalum concentrates, and these were rather low-grade. Commercial production has come mostly from a few mines in the Black Hills and isolated places in New Mexico and Colorado. Mineral collectors' specimen have been obtained in other States, notably Virginia, North Carolina, and New England.

As the United States is the largest consumer of these minerals, its requirements have been largely imported. Columbite has been obtained mostly from Nigeria and tantalite from Brazil and the Belgian Congo. Imports of columbium ore rose to a maximum of 4,277,152 pounds in 1945, and the top figure for tantalum ore was 837,130 pounds in 1944. Both minerals are being stock-piled. Although tantalum ore supplies have recently been more than ample, owing to byproduct production from badly needed beryl in Brazil, the shortages of columbium ores have been serious.

Prices. - In 1946 the principal consumer was offering about 55 cents per pound of contained Cb_2O_5 for columbite with 10:1 ratio of columbium to tantalum and lower prices for lower ratios. During the war, tantalum ores were purchased under a sliding scale. Excluding penalties, the price per pound of Ta_2O_5 ranged from $1.20 for 40-percent grade to $2.55 for 70-percent grade. Trade-journal quotations are usually nominal , owing to the wide range in values of different ores, depending on impurities as well as content of Ta and/or Cb. At the end of 1948 the quotation for tantalum ore, basis 60 percent, was $2 to $2.75 per pound of Ta_2O_5 content. According to the Metal Bulletin (London), columbite ores at the end of 1948 were worth 67 shillings sixpence to 70 shillings per 22.4-pound unit of combined Ta_2O_5 and Cb_2O_5.

Mining and treatment. - Minor amounts of these minerals are recoverable at a few pegmatite mines by hand picking; but mechanical concentration is usually necessary. Owing to their high specific gravity, they are readily recovered by gravity methods along with tin and other heavy constituents, provided the quantities present are sufficient to justify this additional

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treatment. This is often not the case. However, improved recoveries probably can be made (especially at mines where the minerals occur only in small and erratically distributed pockets of finely disseminated grains) by introducing Humphreys spirals or stationary deck tables in the grinding circuits of pegmatite mills. The usual type of jig often is uneconomical when only minute amounts of heavy minerals are to be saved. The mixed concentrates produced by stationary equipment can be cleaned up later on shaking tables and finally separated magnetically or by other suitable means.

GEMS 20/

Prerequisite to being prized as gems, minerals must possess several of the five characteristic qualifications, namely, beauty, durability, rarity, fashion, and portability. Informed persons used to be careful to designate as "precious stones" only the diamond, ruby, sapphire, and emerald; other gems suitable for use in jewelry were called "semiprecious stones," and materials used for statuettes, vases, paper weights, and other decorative objects were termed "ornamental stones". Such distinctions, however, tend to be confusing and are more and more ignored.

Beryl, tourmaline, topaz, spodumene, crystalline quartz and feldspar gems are found in granite pegmatites. The diamond, gem garnet, and olivine originate in basic igneous rocks, and other gems are derived from other types of deposits. The best emeralds have come from metamorphic limestones, but all other varieties of beryl are found almost exclusively in granite pegmatites. Common names for the principal gem minerals found in pegmatites and typical colorations follow:

Beryl: Aquamarine (blue to sea green), golden beryl (also known as yellow beryl or hiliodor), morganite or vorobievite (pink or rose red), goshenite (colorless).

Topaz: (Yellow, also brownish, gray, and pale tints of blue, green, violet, or red).

Tourmaline: Achroite (colorless), rubellite (rose red), Brazilian emerald (green), Brazilian sapphire (blue), Brazilian peridot (yellowish green), peridot of Ceylon (honey yellow), siberite (violet), and indicolite (dark blue).

Spodumene: Kunzite (pink to lilac) and hiddenite (yellow green to emerald green).

Quartz: Rose quartz (pink, rose red), rock crystal (colorless), amethyst (purple, violet), smoky quartz or cairngorm (smoky brown to black), citrine (yellow), siderite (Berlin blue), sagenite or rutilated quartz (contains light-brown needles of rutile), and milky quartz (white).

Feldspar: Orthoclase - adularia (transparent) and moonstone (opalescent); also yellow orthoclase. Microcline - amazonite or amazonstone

20/ Based in part on Gems and Gem Materials, by E. H. Kraus and C. B. Slawson: McGraw-Hill Publishing Co., New York, 1947, 332 pp.

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(jadelike green). Oligoclase - sunstone or aventurine oligoclase (reddish, with bright yellow or red inclusions of iron oxide). Labradorite (gray to blue and green with marked play of colors. Albite - peristerite (similar to labradorite in appearance); moonstone (opalescent).

Miscellaneous: Anatase, rutile, sphene, cordierite, phenacite, chrysoberyl, axinite, apatite, ceylonite, danburite, diopside, zircon.

Rose quartz, smoky quartz, and colorless quartz crystals and amazon stone may occur massive or in large crystals in the main mass of pegmatite. Although rarely found in the parts of a deposit that may be mined principally for feldspar, they are often recoverable by hand-cobbing or on a picking belt. If present in significant proportions, mining operations should be conducted selectively, special care being exercised in blasting to avoid shattering or even unduly straining the gem material. Holes should be drilled well beyond the bodies of visible gem material and loaded lightly. Even heavy sledging may cause damage and develop incipient cracks.

Other gem materials are likely to be found only as linings of vugs or fissures or embedded in clay-filled cavities. The latter modes of occurrence indicate that the gem minerals were formed later than the rest of the pegmatite body, probably much later even than the hydrothermal metallic minerals. Only occasionally can such gemstones be recovered as byproducts of a large-scale pegmatite-mining operation. Blasting may be permissible in driving tunnels or other openings to gain access to the gem-bearing zones, but, when found, these zones are excavated so far as possible by chipping or wedging and prying away the enclosing rock.

As many of the finer gem minerals are heavier and occasionally harder than other pegmatite minerals, it would seem possible, theoretically, to recover them along with tin, tungsten, and/or columbium and tantalum minerals in a heavy mineral concentrate. It is doubtful, however, whether this can ever be done. In the first place, they are rarely found in the pegmatites that are susceptible of mass mining. Moreover, even if present in the original formation, they would probably be damaged in mining or crushing, and the bulk would be so small that efficient recovery would be almost impossible. Gem mines that have been fairly profitable near the surface have often been abandoned as mining costs increased when undecomposed hard rock was encountered below the weathered zone.

Another factor that has contributed to eliminating large-scale gem-mining operations is the probability of high-grading. The usual precautions taken at low-grade gold mines are not applicable to most types of gem mining; even in small-scale operations with a few trusted employees under the watchful eye of the owner or manager, thefts are likely to occur.

Precious stones have been found occasionally in almost every State, but probably the principal output of pegmatite gems in recent years has occurred in California, although substantial amounts are produced irregularly also in Colorado, South Dakota, North Carolina, Maine, and New Hampshire. After about 1909, gem mining of all kinds languished in the United States until the middle 1930's, when it began to revive. This was due in part to

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increased tourist travel by automobile but also to the increased interest in mineral collecting and gem cutting by amateurs and to a greater vogue of colored stones in jewelry. As gems are produced principally by individuals or small partnerships, the entire output in a given locality is often marketed as souvenirs in a local mineral store.

MISCELLANEOUS PEGMATITE MINERALS

Occasionally, a pegmatite quarry will contain such a profusion of minerals as to become a mineral collector's paradise. Owners of some of these deposits have derived a small income from the sale of mineral specimens as well as rose quartz or other ornamental gem material. Owing to the fact that some of these rare minerals are readily identified in pegmatites, it is often believed that further development might discover commercial supplies of ores at greater depth. However, this is not usually the case.

Monazite and other thorium or rare-earth minerals are found in specimen quantities in a few pegmatites but probably never in minable quantities. Partly pegmatized rock masses in Idaho and North Carolina have been considered as sources of monazite, but the unweathered rock is too low-grade to work except at prices far above the recent top figure of around $150 a ton. The world's monazite is likely to come for many years more from beach sands and placer deposits.

Pitchblende and many of its striking alteration products also are found in certain pegmatites, but the average uranium content of pegmatites probably is not much greater than that of parent granites. Most acid igneous rocks contain exceedingly small but conceivably recoverable amounts of both thorium and uranium locked in the molecules of one or more of the common mineral constituents.

Tin and tungsten, on the other hand, have been recovered commercially from pegmatites, although most of the world's production of these metals comes from other types of deposits. Except for one or two deposits in the Black Hills, the percentage of tin present in domestic pegmatites is too small and too erratic to be estimated accurately. Although extensive investigations have failed to discover deposits in the United States that can be worked for tin alone, there is an ever present possibility in certain areas to recover significant amounts of low-grade tin concentrates. Tin is likely to occur in pegmatites that yield spdoumene and can be readily concentrated as a byproduct along with columbo-tantalite and any other heavy minerals, including tungsten.

Small shipments of pollucite have been made from one or more New England pegmatites; the mineral is a rare constituent of other deposits in this country and abroad. In recent years, however, the exceedingly small commercial requirements of caesium have been obtained chiefly from lepidolite, which is a source of rubidium as well as lithium. The rare alkalis are occasionally present in fairly substantial amounts in biotite and other dark micas in and near pegmatites. This occurrence is common enough to justify spectrographic or other examination of dark micas near the contact as well as within the body of the pegmatite itself. Even if present, however, it is doubtful

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whether these elements can be produced under present conditions of meager demand except as minor byproducts.

True primary or residual kaolins have been developed by the decomposition of feldspar in pegmatites, aplites, quartz, micro-porphyry, alaskite, felsites, and micro-granites. The principal source of high-grade primary kaolins of pottery grade in the United States is North Carolina, and these are derived from partly pegmatized alaskite. Primary kaolins have been worked in Latah County, Idaho, and elsewhere, also, chiefly as sources of fire clay. Although the texture of primary kaolins is usually described as much coarser than that of sedimentary or transported kaolins, this texture is due mainly to the grit content. After removing quartz and other nonclay minerals, the average particle size of the kaolin itself is likely to be rather small, perhaps too small to be acceptable to paper makers. Our main supplies of paper clay come from sedimentary deposits in Georgia and South Carolina.

CONCLUSIONS AND RECOMMENDATIONS

To engineers and investors accustomed to thinking in terms of modern mass mining operations, the outstanding facts about pegmatite ventures in the past have been the relatively small size and great irregularity of deposits, the difficulty of sampling accurately, and, consequently, the seeming impossibility of developing measured reserves large enough to assure uniform mill feed long enough to permit amortizing the capital investment. New knowledge regarding the internal structure of pegmatites has already eliminated some of the guesswork and holds promise of placing pegmatite mining on an even footing with other kinds of mining as regards estimating reserves and forecasting financial gains or losses after systematic exploration and development.

Predictions are always hazardous, but in the foreseeable future it would seem that pegmatite-mining ventures most likely to prosper are those that most nearly conform to American conditions of economical production. It is unreasonable to suppose that mass production methods can be employed in any pegmatite operation on a scale comparable to the huge operations at porphyry copper or iron ore mines, but it is equally unreasonable to expect that even a small mining operation can be conducted successfully in the United States under present labor conditions unless hand work is replaced by machines whenever economically possible. The signs are plain that the changing economic climate is becoming more and more unfavorable to small-scale operations. The problem, then, is to establish the industry so that it will attract larger capital investment, permit the use of modern, efficient tools, and employ recent advances in technology and managerial "know-how."

Only occasionally is it possible to find a single pegmatite deposit large enough to justify the purchase of extensive mining equipment or the construction of a suitable mill for economical recovery of all the useful minerals in the ore. However, this does not mean that pegmatite mining must forever remain a composite of small, uneconomical units. In most districts it is possible to develop enough prospects within a radius of a few miles so that the aggregate tonnage in sight may be enough to amortize a substantial

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capital expenditure. It thus becomes possible to erect a central mill and to develop a fairly effective mining organization with portable compressors and other equipment that can be moved readily to a new location when one deposit is worked out or becomes unprofitable to mine. Another important advantage of basing operations on a number of different deposits is the fact that the entire enterprise is no longer dependent on the vagaries of a single erratic formation. Instead of putting all the eggs in the same basket, the risk is reduced roughly in proportion to the increased number of chances. Moreover, by operating two or more deposits simultaneously, more working faces can be obtained and larger tonnages extracted than would be possible in a single small deposit.

Although traditional methods of sampling and evaluating reserves may not yet have been perfected so as to be applied universally to all pegmatites, enough engineering work should be done on a given deposit or group of deposits to afford reasonable assurance as to the quantity and nature of the "ore". If zoning is observed or suspected the core drilling and other exploration should be guided accordingly. There may be times, however, when local experience and the general history of the district may prove to be the best guide. It is assumed too generally nowadays that so-called "practical men" merely practice the mistakes of their predecessors. Until we know more about the vagaries of pegmatites, the professional geologist or mining engineer should not ignore the testimony of local mining men. On the other hand, the final decision as to minimum available tonnage should be based upon something more tangible than hearsay evidence or wishful thinking. Moreover, enough sampling should be done to demonstrate the probable variation in character and proportionate distribution of the principal minerals, and enough mineral-dressing tests should be made to prove that such mixtures can be milled successfully. As a general rule, too much emphasis should not be placed on possible recovery of products other than feldspar and perhaps scrap mica or spodumene. This does not mean that possible recovery of beryl, tin, or other byproducts should be neglected, merely that experience has shown that in most deposits the distribution of such minor constituents may be too erratic for even approximate estimation. Based upon the zonal theory, it may be possible to make dependable estimates of reserve tonnages of even these minor constituents but for the present the safest policy is to be conservative. Owing to the relatively small amounts of these rarer elements in most dikes, the increment of value from their recovery generally falls within the margin of error in calculating returns from major products.

An elementary principle of industrial economics that applies with special force to many of the mineral industries is vertical integration. By producing better and cleaner products and by extending operations somewhat into the manufacturing field, the mining industry often obtains a large share of the ultimate consumer's dollar. Here again, however, the small operator is handicapped. Most processing equipment cannot be employed successfully unless it can be operated virtually full time and unless the volume of material exceeds an economical minimum. Then, of course, more capital is required when ground feldspar, for example, is the final product rather than crude spar. Not only must additional equipment be bought, but working capital is needed to finance material in process and to maintain

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sales effort. Whereas day-to-day fluctuations in the quality of the product may be tolerated when sales are made to a custom mill, ultimate consumers are much more exacting in their specifications and have a right to expect regular and uniform deliveries. This means careful control of operations and sometimes it calls for stock-piling of several grades of material and proper blending.

The casual reader of the foregoing pages will doubtless be impressed by the fact that pegmatite operations in the past have not usually been profitable and that they often are quite risky. This is true. On the other hand, better understanding of the geology of these interesting deposits, expanding markets for several of the products, and vastly improved milling methods are tending to reduce some of the major hazards and uncertainties and thus point the way to the establishment of pegmatite enterprises that should prove highly profitable when soundly planned and intelligently operated.

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